SYSTEM TO DETECT AND REDUCE WIDE-ANGLE SEISMIC REFLECTIONS AT SEA.

BY

Stuart Kaufmann Edleson

United States Naval Postgraduate School

THESIS

SYSTEM TO DETECT AND REDUCE
WIDE-ANGLE SEISMIC REFLECTIONS
AT SEA

by

Stuart Kaufmann Edleson, Jr.

September 1970

System to Detect and Reduce

Wide-Angle Seismic Reflections

At Sea

by

Stuart Kaufmann Edleson, Jr.
Lieutenant Commander, United States Navy
B.S., Iowa State University, 1962

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
September 1970

ABSTRACT

A simple system was designed to collect wide-angle reflection records in order to investigate the interval sound speeds of the sediment layers in the ocean. The system consisted of a frequency modulated receiver, a cut-to-channel Yagi antenna, and a sonobuoy, used in conjunction with a precision sonic profile recorder and a triggered sound source. A computer routine for reducing the data was obtained and modified for compatibility with the system and use on the IBM 360/67 computer. The system was designed to be both inexpensive and simple to use without any loss of accuracy.

TABLE OF CONTENTS

I. INTRODUCTION 9

II. BACKGROUND 11

III. THE WIDE-ANGLE REFLECTION METHOD 12

A. THE THEORY 12

B. THE MATHEMATICAL MODEL 14

1. Forming the T/X Plot 14

2. Determination of Interval Sound Speed 20

a. First Layer 22

b. Second Layer 25

C. THE COMPUTER PROGRAM 32

1. Data Reduction 33

2. Trial Solutions 36

IV. INSTRUMENTATION 38

A. THE WIDE-ANGLE REFLECTION SYSTEM 38

1. The Sonobuoy 38

2. The Receiver System 46

V. CONCLUSIONS 53

APPENDIX A: DIGITIZING THE WIDE-ANGLE REFLECTION RECORD 54

APPENDIX B: ROUTINE FOLLOWED BY HONDO I COMPUTER PROGRAM 57

APPENDIX C: HONDO I COMPUTER PROGRAM 66

APPENDIX D: SAMPLE DATA 79

APPENDIX E: RESULTS 80

LIST OF REFERENCES 85

INITIAL DISTRIBUTION 86

FORM DD 1473 87

LIST OF TABLES

I.	Comparison of Solutions of SLOW I and HONDO I Computer Programs	34
II.	Comparison of Results of Various Trial Solutions	37
III.	Sonobuoy Frequencies	40
IV.	Sonobuoy Characteristics	42

6 (Blank)

LIST OF FIGURES

1.	Wide-angle Reflections	13
2.	Ray Paths and T/X Curves for Rays Reflected from a Horizontal Surface	15
3.	Ray Paths and T/X Curves for Rays Reflected from a Plane Dipping Surface	19
4.	T_o Reflection from the Second Layer	27
5.	Multiple Reflections	35
6.	System for Collecting Wide-angle Reflections	39
7.	AN/SSQ-57 Sonobuoy	41
8.	Releasing the Bottom Plate of the AN/SSQ-57 Sonobuoy	44
9.	Bottom Plate Retaining Clips	45
10.	Removing the Rotochute Assembly	47
11.	Yagi 11-element Antenna	49
12.	Power Gain vs. Frequency Curve	51
13.	Antenna Patterns for Yagi Antenna at Various Frequencies (Relative to 175 MHz)	52
14.	Digitizing the Data	55
15.	Relating Direct Travel Time to Corresponding Reflected Travel Time	60

ACKNOWLEDGEMENTS

The author wishes to extend his sincere appreciation to his advisor, Professor Robert S. Andrews, who originally suggested the topic and provided immeasurable assistance in delimiting the scope of the problem. My appreciation is also extended to Mr. Robert C. Smith of the Research Administration Electronics Laboratory at the Naval Postgraduate School for his assistance in building and testing various electronic components required in the course of the study; to Mr. Robert E. Houtz at the Lamont-Doherty Geological Observatory of Columbia University whose correspondence provided invaluable assistance in developing the system and writing the computer program; and to Dr. Roland von Huene and Mr. Harry Hill, both of the Marine Geology Division of the U. S. Geological Survey, Menlo Park, for their technical advice and various equipment and services they made available for testing and evaluating the system. My special thanks are due to Miss Dianne Williams whose love and moral support aided the study considerably.

I. INTRODUCTION

The objective of this study was to develop a simple yet inexpensive system for collecting wide-angle reflection data. This system would be used in conjunction with normal-reflection profiling equipment normally carried on board oceanographic survey vessels. The study involved testing an inexpensive radio receiver to be used to receive a signal transmitted by a sonobuoy with enough clarity that the signal could be recorded on a precision seismic graphic recorder. The study also involved testing and launching five sonobuoys and investigating modifications which can be made to the sonobuoys to enhance the success of the system.

A further objective of the study was to provide a method for reducing the data collected by the system and obtaining the mean sound speed existing between successive reflectors (called the interval sound speed of the layer defined by an upper and lower reflector) and the thicknesses of the corresponding sub-bottom layers. This required modifying an existing program to read the data and compute the results on the IBM 360/67 digital computer using FORTRAN IV language.

This paper presents a short discussion of the background and purpose for developing a system for collecting wide-angle reflection data and obtaining a program to reduce the data and determine the interval sound speeds. A theory of wide-angle reflections is offered, together with a mathematical model used to develop the equations and

suggest a method of solution. The computer program is discussed, including the method of digitizing data from a wide-angle reflection record. The radio receiver, antenna, and radio sonobuoy used to develop the system for use in conjunction with normal-reflection equipment is discussed. In the last section, conclusions and suggestions for further work on the subject are offered.

II. BACKGROUND

The geological structure and composition of the sub-bottom layers in and around Monterey Bay are presently known to only a limited extent. Sufficient depth recordings have been made to enable drawing a detailed relief map of the sea floor; and shallow cores and grab samples have been analyzed for determination of the composition of the sediments in the first few meters. But knowledge of the deeper layers has been restricted to only subjective analysis involving the extrapolation of the immediate terrestrial structure from wells and outcrops and correlating the data with normal-reflection seismic profiling data. Unfortunately, normal-reflection profiles measure only the travel times and relative intensity of the vertical reflections. Without knowledge of the sound speed-depth relationship, only a guess can be offered as to the actual sub-bottom structure. A knowledge of the sound speed-depth variation is essential to a quantitative evaluation of the sediment layers and to a geological interpretation relating sound speed to type of material, age, and consolidation (Le Pichon, Ewing, and Houtz, 1968).

The system developed for collecting wide-angle reflection data along with the computer program to reduce the data can provide information on the sound speed-depth relationships and the layer thicknesses.

III. THE WIDE-ANGLE REFLECTION METHOD

The characteristic feature of the wide-angle reflection method is the measurement of the travel times of longitudinal waves which have been reflected at boundaries separating media of different acoustic impedances (the product of sound speed and density). From measurements of reflection times it is usually possible to determine the depths and dips of the reflection horizons and the speed of the seismic wave (Jakosky, 1949).

A. THE THEORY

The system was developed based on the theory that a sound produced at source S (Fig. 1) will reach the hydrophone of the sonobuoy B by three different ray paths as shown; 1 the direct ray which travels just below the surface of the water, 2 the sound reflected from the water-sediment interface, and 3 the sound waves reflected from the various sediment layers that may exist below the ocean floor. If the distance separating the sound source and the hydrophones is steadily increased while the source emits sharp sound pulses at regular intervals, the time difference between the arrivals of the direct and reflected sound waves will change depending on the sound speed-depth variation within the sediments. A record of time differences is used to compute the thicknesses and interval sound speeds of the various layers and obtain the sound speed-depth relationship.

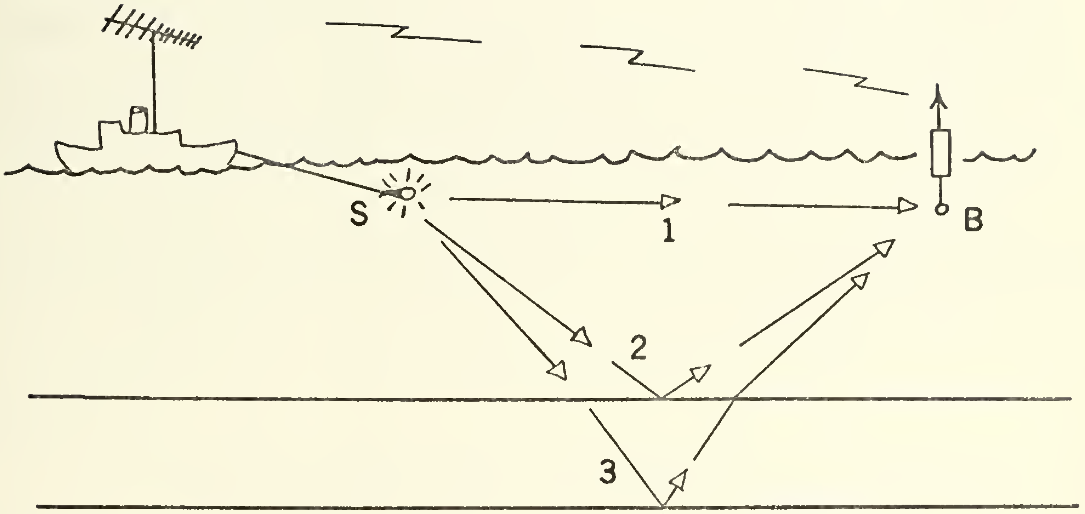


Figure 1. Wide-angle reflections

B. THE MATHEMATICAL MODEL

1. Forming the T/X Plot

For the purpose of forming an elementary concept of the reflection method and to illustrate the formation of the wide-angle reflection records, it is useful to first consider a simple case of a single layer of homogeneous isotropic material of uniform thickness H. It follows from this case that the ray paths will follow straight lines. A further assumption may be made that the lower surface reflects the sound wave in accordance with the physical laws of optics so that the angle of reflection is equal to the angle of incidence. Also it will be assumed that the path taken by sound passing from one media to another having a different sound speed is refracted in accordance with Snell's Law.

Figure 2 illustrates a single layer model with a water medium of depth H and average vertical sound speed V. The theoretical travel time on the record for a vertically-propagating sound wave when the sound source and sonobuoy are at the same point S in the ocean is referred to as T_o. Thus T_o defines the origin of the record at which point the direct travel time is zero. The source sound wave will propagate downward through the water to point A and then be reflected back to the sonobuoy in time

$$T_o = \frac{2H}{V} \quad . \tag{1}$$

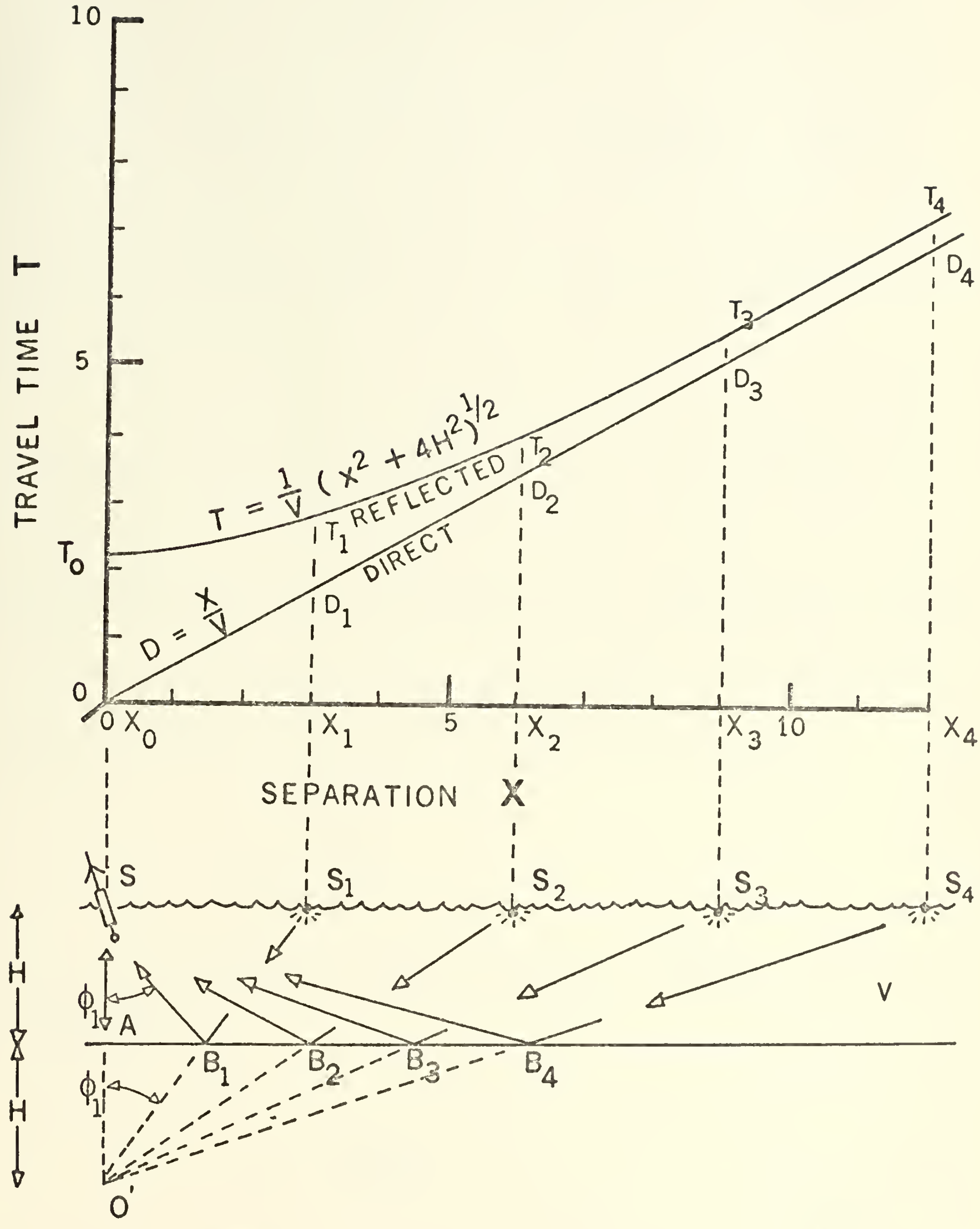


Figure 2. Ray paths and T/X curves for rays reflected from a horizontal surface

If an anology is made to the laws of geometric optics, the ray paths may be conveniently handled by utilizing the concept of images. The travel time to the theoretical image point 0' is equal to the time for the reflected ray to return to the sonobuoy. Therefore, when a mathematical model is constructed, the reflected times can be considered as the time required for the sound to travel from any shot point S_i to the image point 0' at a sound speed of V.

At shot point S_1, a sound wave travels to point B_1 where it is reflected upward to the sonobuoy. This wave is referred to as the reflected ray from the first reflector. The direct ray travels horizontally from the source to the sonobuoy at S. Again using the concept of images, the reflected ray path S_1B_1S is equal to the assumed path S_1B_10' (path length R_1) and the travel time becomes

$$T_1 = \frac{R_1}{V} , \qquad (2)$$

where T_1 is the travel time of a reflected ray. From the geometry of the triangle SB_1A

$$R_1 = \frac{2H}{\cos\phi_1} . \qquad (3)$$

Equation (2) then becomes

$$T_1 = \frac{2H}{V\cos\phi_1}, \qquad (4)$$

where ϕ_1 is the angle of incidence measured from the vertical.

The direct ray arrives at the sonobuoy at time

$$D_1 = \frac{X_1}{V}, \qquad (5)$$

where D_1 is the travel time of a direct ray, X_1 is the separation between the shot and the sonobuoy, and V is the sound speed.

In general, the separation X can be related to the depth H and the length of the reflected ray path by use of the Pythagorean Theorem; i.e.,

$$X^2 = R^2 - 4H^2, \qquad (6)$$

where R is the distance from the shot point to the image point 0'.

As successive shots are fired while steadily increasing the separation, the record of the direct travel times results in a straight line on the T/X plot shown in the upper half of Figure 2. From Equation (5) it can be seen that the slope of this line is the reciprocal of the water sound speed. The record of the arrival of the reflected rays form a hyperbola asymptotic to the direct travel time line at large values

of X. Equation (6) can be combined with the relation

$$T = \frac{R}{V} ,$$

where T is the travel time of the reflected ray and V is the sound speed to obtain the equation of a hyperbola

$$T = \frac{1}{V} (X^2 + 4H^2)^{1/2} . \tag{7}$$

For a bottom with a slope shown in Figure 3, it can be shown that an additional term is introduced into the above equation. The equation for the reflected travel time for such a model is

$$T = \frac{1}{V} (X^2 + 4H^2 + 4HX \sin \theta)^{1/2} \tag{8}$$

where θ is the angle of slope of the bottom. The sign of the additional term is negative if the bottom dips in the direction opposite to that shown in Figure 3.

If a mean sound speed between the sea surface and any sub-bottom reflector is considered, it will be realized that the record of reflection times from that reflector will also form a hyperbolic trace on the T/X graph in accordance with Equation (7), with V equal to the mean sound speed between the surface and the reflector and H equal to the depth to the reflector. The mean sound speed V can be calculated, but it provides little information for determining the sound speed-depth

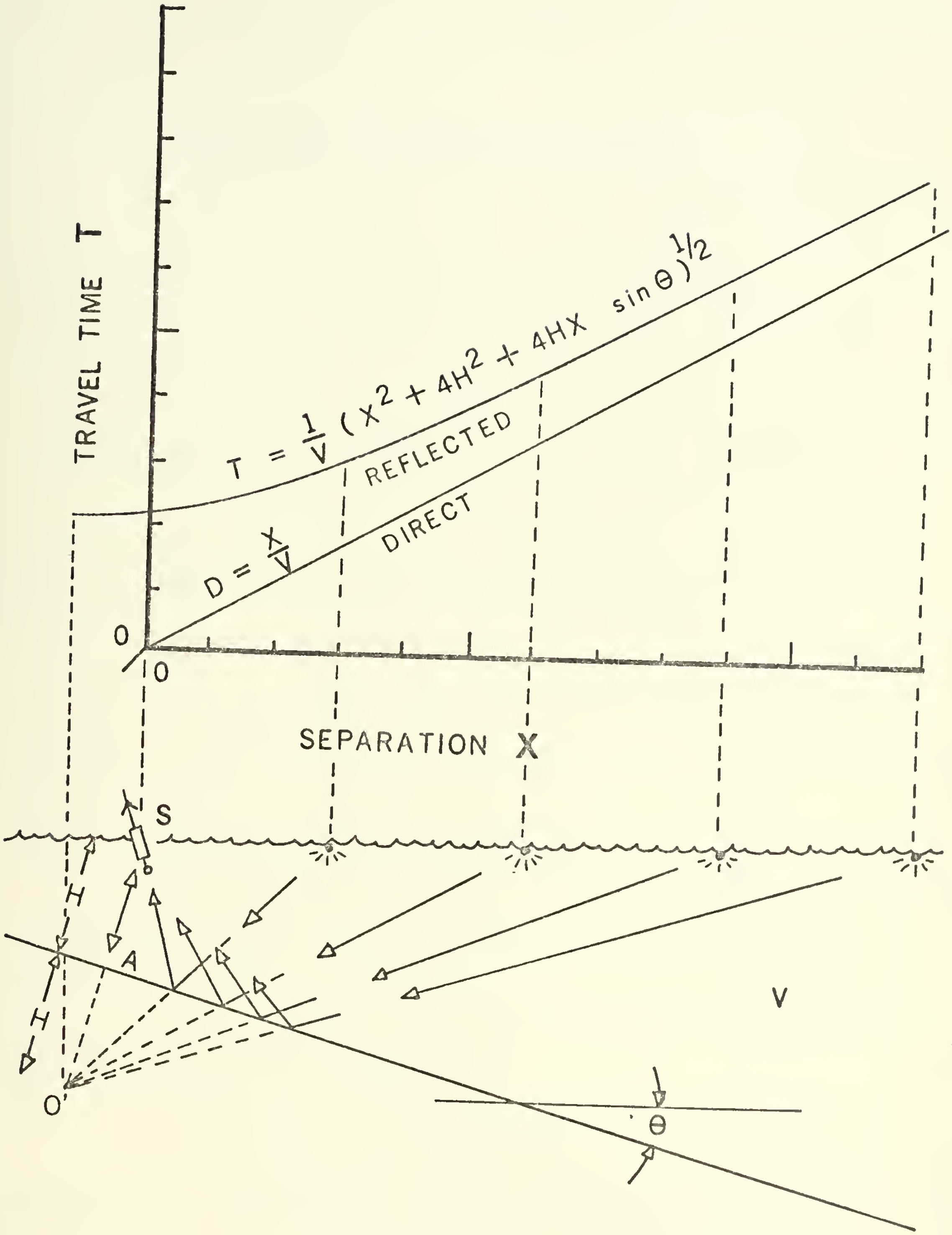


Figure 3. Ray paths and T/X curves for rays reflected from a plane dipping surface

relationship. The sound speed that is required for determining this relationship, however, is the interval sound speed of the layer defined by an upper and lower reflector.

2. Determination of Interval Sound Speed

The determination of the interval sound speeds by reflection measurements is an old geophysical problem (Clay and Rona, 1965) and techniques for reducing the data go back a number of years (Green, 1938). The method of determining the interval sound speeds between successive reflecting layers from wide-angle reflection data is presently quite well known and has been described extensively in the literature (Dix, 1955). Its use at sea has been discussed by Houtz and Ewing (1963), Knox (1965), Clay and Rona (1965), and Le Pichon, Ewing, and Houtz (1968), among others. The method used in this paper follows the technique introduced by Le Pichon, Ewing, and Houtz (1968) and is the method used in the computer program of Appendix A.

The water layer is assumed to have a known sound speed-depth profile, with the horizontal sound speed at the surface V_h different from that of the sounding speed (the sound speed integrated over the depth H of the water layer).

It is further assumed that the dip of the bottom is known. The dip of any sub-bottom layer will be considered here to be the angle between the upper and lower reflectors defining the layer. Dip is considered positive if the distance between the two reflectors increases

in the direction of separation between source and receiver. The dip of the water layer illustrated in Figure 3, for example, is positive.

Assuming such a dip and using a mean water sound speed equal to the sounding speed V_1, Equation (8) can be rewritten as

$$T^2 = \frac{1}{V_1^2} (X^2 + 4H^2 + 4HX\sin\theta), \tag{9}$$

and Equation (1) becomes

$$T_o = \frac{2H}{V_1} . \tag{10}$$

Since the direct travel times are a function of the horizontal sound speed V_h, Equation (5) becomes

$$D = \frac{X}{V_h} . \tag{11}$$

Substituting Equation (10) and (11) into Equation (9) and rearranging terms, an equation relating the reflected travel time to the direct travel time is

$$T^2 = T_o^2 + \left(\frac{V_h}{V_1}\right)^2 D^2 + 2T_o \left(\frac{V_h}{V_1}\right) D \sin\theta . \tag{12}$$

If V_1 is replaced by the mean vertical sound speed of the material contained between any two reflectors, called the interval sound speed V_{i+1}, Equation (12) will relate the reflected travel time within the layer to the direct travel time at the surface corresponding to the

reflected time. The subscript i+1 indicates the sound speed for the i-th sub-bottom layer. The wide-angle reflection records, however, relate total reflected travel time to total direct travel time.

The technique used to solve for the interval sound speed involved reducing the travel times for effects of the upper layers in order that the reduced values have the form of Equation (12). An iterative method is then used to reduce the effect of dip by eliminating the curvature term β of Equation (12); i.e.,

$$\beta = 2T_o \left(\frac{V_h}{V_1}\right) \sin \theta. \tag{13}$$

Finally, a least-squares line is fitted to the reduced $(T^2 - T_o^2)/D^2$ data and the coefficient

$$\left(\frac{V_h}{V_{i+1}}\right)^2$$

is determined. From this, the interval sound speed is readily determined.

a. First Layer

The water between the surface of the ocean and the sea floor is considered here to be the first layer. It is assumed that the dip of the sea floor θ_1 is known and the sounding speed V_1 can be determined with good accuracy.

Knowing V_1 and θ_1 and knowing the reflected travel times as a function of the direct travel times from the T/X data, the

solution of the first layer involves computing the thickness of the water layer H_1 and the horizontal sound speed at the surface V_h.

If data are obtained close to T_o, a fourth-order least-squares polynomial is fitted to the T/X data,

$$T = a_o + a_1 D + a_2 D^2 + a_3 D^3 + a_4 D^4 , \tag{14}$$

where the a's are coefficients of the polynomial. At reflected travel time, T_o, the direct travel time D is zero; the reflected travel time, also being the minimum travel time for the reflected wave, is equal to the coefficient a_o; i.e.,

$$T_o = a_o . \tag{15}$$

The fourth-order curve is then extrapolated, obtaining the minimum reflection time T_o.

Care must be used with this method because the least-squares fitting technique does not constrain the fourth-order curve beyond the limits of the data. A more reliable but less accurate method is to fit the T^2/X^2 data to a linear least-squares line of the form

$$T^2 = b_o + b_2 D^2 . \tag{16}$$

Again it can be shown that the coefficient b_o is equal to T_o^2. Thus, T_o is obtained by extrapolating a straight line instead of a curve as was done in the case of the fourth-order polynomial.

The computer program used to reduce the T/X data decides which of the above two methods will be employed to solve for T_o. Three-tenths of a second direct travel time was considered the maximum allowable distance from which the curve could be extrapolated using the fourth-order polynomial.

Having computed T_o and knowing V_1, the depth of the layer H_1 is computed using Equation (1).

The curvature term in Equation (12) is small compared to the other two terms and, therefore, little error is introduced by assuming V_h/V_1 equal to unity. This assumption is used to define a correction term to be applied to Equation (12); i.e.,

$$\Psi = T_o^2 + 2T_o (1) \sin \theta \tag{17}$$

The reduced travel times T_r are then computed for each data point using the relation

$$T_r^2 = T^2 - \Psi \quad . \tag{18}$$

Combining Equations (12) and (18), the expression for T_r becomes

$$T_r^2 = \left(\frac{V_h}{V_1}\right)^2 D^2, \tag{19}$$

where T_r is a reduced travel time with the effects of both the dip and T_o eliminated. The horizontal water sound speed V_h is then found by fitting T_r^2 and D^2 to a least-squares first-order line of the form

$$T_r^2 = c_1 D^2 , \tag{20}$$

and solving for the coefficient c_1. Knowing V_1, Equation (19) can be solved for V_h; i.e.,

$$V_h = V_1 \sqrt{c_1} \quad . \tag{21}$$

The separation X is then computed using Equation (5),

$$X = DV_h \tag{22}$$

b. Second Layer

The second layer is, in fact, the first layer of sediments for which an interval sound speed is desired. The record of reflected travel times from the lower interface of the second layer T_2 forms a hyperbola similar to that of the first layer. In the first layer the interval sound speed V_1 was known and the separation X was computed for each point. In the second layer, the interval sound speed V_2 is unknown, but the reduced direct travel time can be deduced by reducing the effects of the first layer on the travel times of the second layer.

The thickness of the second layer H_2 is computed using assumed values for the interval sound speed V_{2_a} and dip θ_{2_a} of the layer. These values are referred to as the trial solution for the second layer. The trial solution is based on the apparent dips read on the normal reflection profiles, converted to true dips using trial sound speeds. The exact value of these trial sound speeds are not critical, so long as they are consistent with the dips entered.

In Figure 4, an assumed ray path is drawn as the dashed line $\overline{SBC}$. This ray is perpendicular to the second reflector; i.e., to the lower interface of the second layer. From Snell's Law

$$\sin \phi = \left(\frac{V_1}{V_2} \sin \theta_2\right). \tag{23}$$

The distance the ray travels in the first layer $\overline{SB}$ is therefore

$$\overline{SB} = \frac{H_1}{\cos \phi} , \tag{24}$$

and the time T_1 in the first layer

$$T_1 = \frac{\overline{SB}}{V_1} , \tag{25}$$

where V_1 and H_1 are both known.

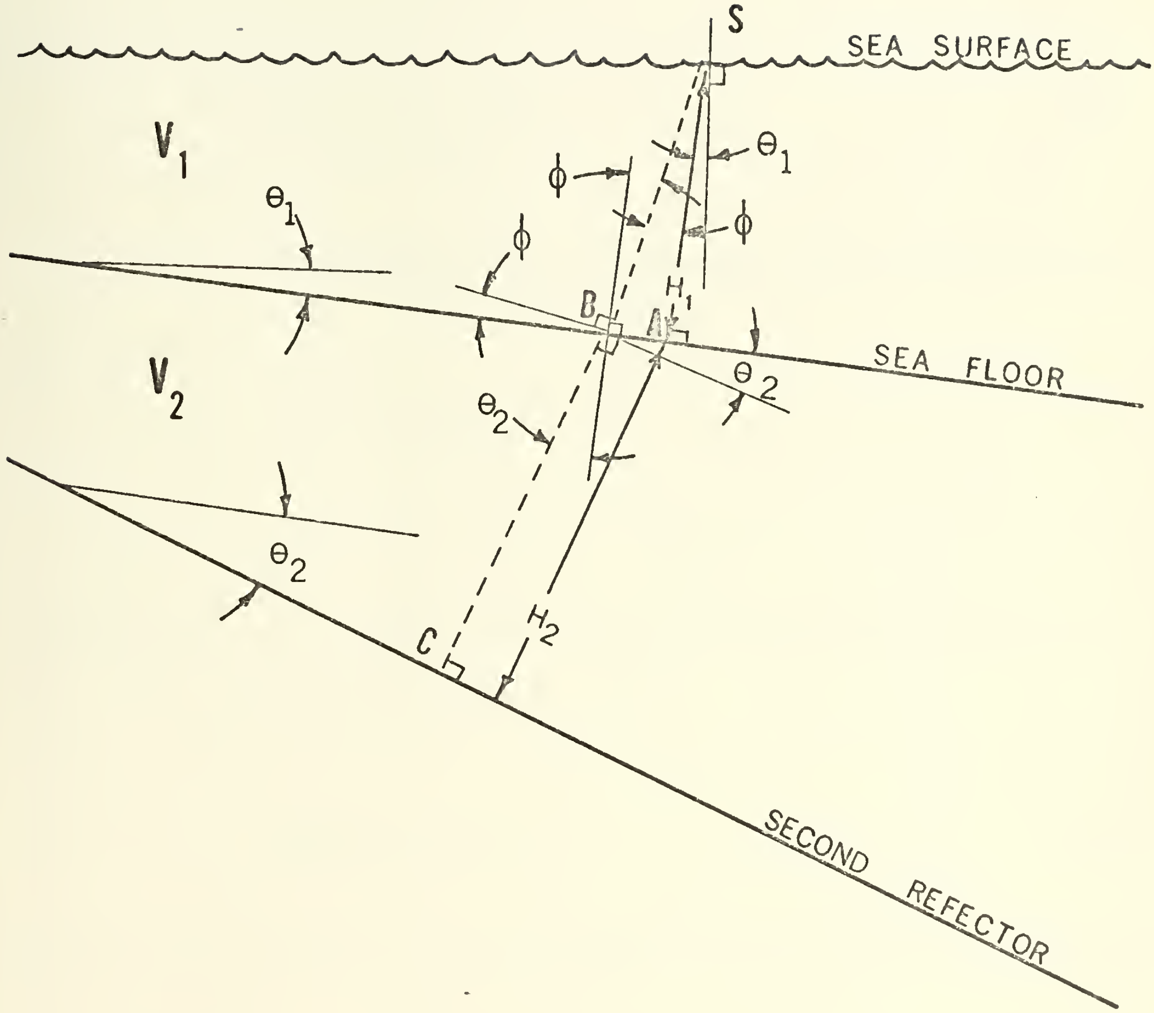


Figure 4. T_o reflection from the second layer

To obtain the reduced minimum travel time $T_{o_{2_r}}$ for the second layer alone, the minimum measured time to the second reflector T_{o_2} (obtained fitting the data to a least-squares polynomial) must be reduced by the time the sound traveled in the first layer T_1,

$$T_{o_{2_r}} = T_{o_2} - T_1. \tag{26}$$

The length $\overline{BC}$ is obtained using the trial sound speed V_{2_a},

$$\overline{BC} = V_{2_a} T_{o_{2_r}} . \tag{27}$$

The length $\overline{AB}$ is the distance the direct ray will travel corresponding to the distance $\overline{SB}$ the reflected ray travels in the first layer. $\overline{AB}$ is computed from the expression

$$\overline{AB} = H_1 \tan \phi, \tag{28}$$

and the depth of the second layer H_2 below the shot point S at reflected travel time T_o is

$$H_2 = \overline{BC} + \overline{AB} \sin \theta_2 . \tag{29}$$

H_2 is a first approximation for the thickness of the second layer.

Since V_h was computed for the first layer, Equation (14) can be written as

$$T = d_o + d_1 X + d_2 X^2 + d_3 X^3 + d_4 X^4, \tag{30}$$

where

$$X = DV_h,$$

and

$$d_i = \frac{a_i}{V_h} .$$

Differentiating with respect to X, the horizontal separation, Equation (30) becomes

$$\frac{dT}{dX} = d_1 + 2d_2X + 3d_3X^2 + 4d_4X^3 . \tag{31}$$

It can be shown (Clay and Rona, 1965) that the angle of emergence at the sea surface $\emptyset+\theta$, is related to the derivative by

$$\frac{dT}{dX} = \frac{\sin (\emptyset + \theta_1)}{V_1} . \tag{32}$$

The data from the T/X graph is fitted to a fourth-order least-square polynomial and the coefficients of Equation (30) determined.

The angle $(\emptyset+\theta)$ is computed for each data point by combining Equations (31) and (32) to give

$$\sin(\emptyset + \theta_1) = V_1 \; (d_1 + 2d_2X + 3d_3X^2 + 4d_4X^3). \tag{33}$$

Knowing the dip of the first layer θ_1, $\emptyset$ is easily obtained.

From $\emptyset$, and using the sounding speed V_1, the travel time of the second reflected ray within the first layer is computed. This is then subtracted from the total reflection time to obtain the reduced reflected travel time T'_{2_r}, the time the reflected sound from the second reflector travels within the second layer. Similarly, a reduced direct travel time D_r is obtained and from Equation (5), the reduced separation X_r. Thus, the effects of the first layer are eliminated for each point and the problem reduced to a single layer case.

The effect of dip is removed in a way similar to that used for the first layer. Equation (17) becomes

$$\Psi = T^2_{o_{2_r}} + 2T_{o_{2_r}} \left(\frac{X_r}{V_{2_a}}\right) \sin\theta_{2_a}, \tag{34}$$

where

$$X_r = V_h D_r, \tag{35}$$

and the subscript 'a' indicates the assumed values of the trial solution of V_2 and θ_2. The reduced times corresponding to the flat layer case T_{2_r}

are obtained from

$$T_{2_r} = T'_{2_r} - \Psi \qquad . \tag{36}$$

The reduced values are then used to compute the co-efficients of a straight line equation of the form

$$T^2_{2_r} = k_o + k_1 X^2_r \; , \tag{37}$$

where k_o should be zero because Ψ in Equation (36) eliminates $T_{o_{2_r}}$ and

$$k_1 = \frac{1}{V^2_2} \quad , \tag{38}$$

and V_2 can be readily computed. The dip θ_{2_a} is then corrected by

$$\tan \theta_2 = \frac{V_2}{V_{2_a}} \tan \theta_{2_a} \; . \tag{39}$$

The solutions for V_2 and θ_2 then replace the original trial solutions and the process is iterated a second time. A final solution is obtained for V_2, θ_2, and H_2 and the computations move on to the next layer.

Thus, in the first layer, knowing the sounding speed V_1 and the dip θ_1, and having the record of reflected travel times T_1 verses direct travel times D_1, the value of the water depth H_1 and

horizontal sound speed V_h were computed. In the second layer, the problem was reduced to finding the interval sound speed V_2 and the thickness H_2 by eliminating the effects of the first layer and then reducing the effect of dip using a trial solution. In each successive layer, the problem is first reduced to a single layer case by eliminating the effects of all upper layers using the computed values of thicknesses and interval sound speeds of those layers, and then the effect of dip is subtracted using an iterative process and a trial solution.

This method is both fast and accurate. The time to reduce the data from a typical station is usually less than 20 seconds on the IBM 360/67 digital computer and the theoretical accuracy obtained is better than 1 part in 10,000 if the proper dips are entered (Le Pichon, Ewing, and Houtz, 1968). The primary advantage of this method is that there is no requirement that the layers be parallel, but rather, they may be dipping with respect to one another.

C. THE COMPUTER PROGRAM

The HONDO I program used to reduce the wide-angle reflections is listed in Appendix C. It was adapted from a similar program used at Lamont-Doherty Geological Observatory (LGO) of Columbia University (Houtz, personal communication) and follows the mathematical technique just presented of solving for thickness and interval sound speed of successive sub-bottom layers. Certain modifications were necessary to make the program compatible with the wide-angle reflection system

developed and for use in conjunction with the IBM 360/67 digital computer at the Naval Postgraduate School (NPS) using FORTRAN IV language. A thorough description of the routine followed by the program is presented in Appendix B.

Sample data were included with the LGO program and modified accordingly (Appendix D) to be used with the HONDO I program. The corresponding results (Appendix E) were compared with those obtained using the IBM 1130 digital computer at LGO and the original form of the program, SLOW I. No significant difference was observed between the two solutions. The results from both programs are given in Table I.

1. Data Reduction

Instructions for entering the data on IBM cards are included on the first page of the HONDO I program list. A more delicate part of the data reduction consists of selecting and tracing the major reflectors from the precision seismic graphic record made during the field profiling. Here special care must be taken to avoid multiples that can occur and to use only those traces representing the events from true lithological reflectors. The difference between true reflectors and multiples is shown in Figure 5. It was assumed that the interval sound speed increased with depth. The apparent reflection times from multiples at a given separation are greater than those of the corresponding true reflector because the multiple travels longer in the lower speed layer than the true reflector. Note also, the T/X trace of the multiple is nearly parallel to the true reflection from the same reflector. Results that are not

Table I

Comparison of Solutions of SLOW I and HONDO I Computer Programs

Layer	SLOW I (LGO)	HONDO I (NPS)
FIRST LAYER:		
Reflection Time (seconds)	5.216	5.216
Sound Speed (km/sec)	1.490	1.490
Propagated Error (km/sec)	±.0023	±.0023
Depth (meters)	3885.9	3885.9
SECOND LAYER:		
Reflection Time (seconds)	5.805	5.805
Sound Speed (km/sec)	1.797	1.7861
Propagated Error (km/sec)	±.0608	±.0597
Thickness (meters)	529.22	526.28
THIRD LAYER:		
Reflection Time (seconds)	6.250	6.250
Sound Speed (km/sec)	1.770	1.7875
Propagated Error (km/sec)	±.0951	±.0952
Thickness (meters)	379.83	398.16

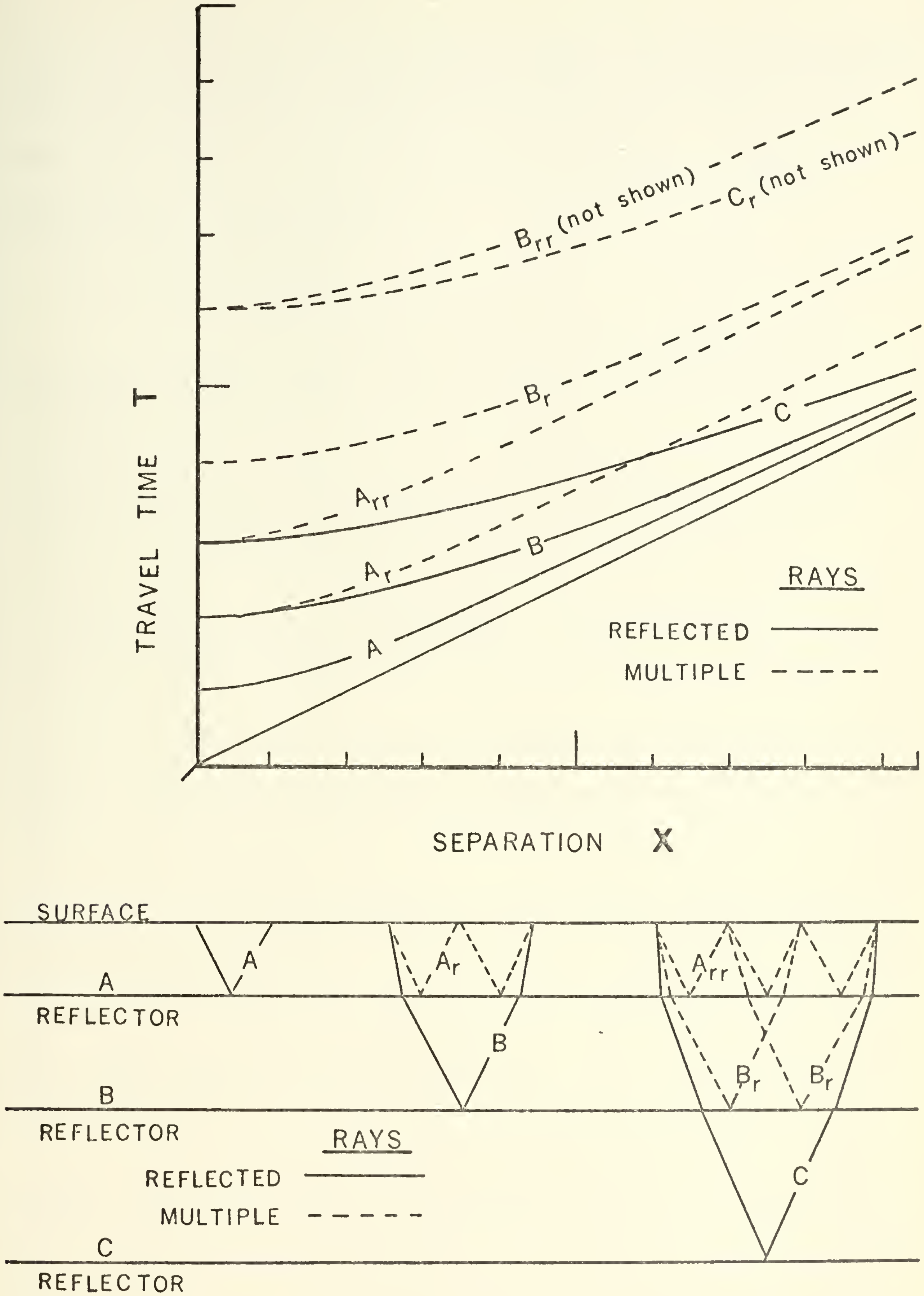


Figure 5. Multiple reflections

consistent with the local geology present another indication that multiples were present and traced. After the true reflectors are determined, the wide-angle reflection record is digitized in accordance with the procedure outlined in Appendix A.

2. Trial Solutions

As discussed previously, the trial solutions are obtained from normal profiling records. The trial values of interval sound speed and dip for each successive layer are entered on IBM cards in accordance with the instructions listed in Appendix C. If the interfaces are horizontal, there are no corrections for dip in the computations and the values for interval sound speed are unimportant. If the interfaces are not horizontal, inaccurate estimates of the sound speeds lead to only small errors in the first iteration and become negligible by the second iteration. However, dips entered which are inconsistent with the trial interval sound speeds may result in large errors. The error caused by entering such inconsistent values was investigated and the results given in Table II. The true solutions were those values computed using the data as given in Appendix D. The values computed in Case A were obtained assuming a trial sound speed 0.1 km/sec greater than the given data for both the second and third layers. For Case B, the trial sound speeds were unchanged, but the dips of the second and third layers were entered as $+1.0^{\circ}$. It can be seen from Table II that the error introduced by incorrect sound speeds is small, but entering dips inconsistent with the trial sound

speeds causes significant error. Furthermore, the computer program will not detect such errors but will compute values consistent with the dips entered.

Table II

Comparison of Results of Various Trial Solutions

	Computer Sound Speed (km/sec)		Propagated Error (+km/sec)	
	Second layer	Third layer	Second layer	Third layer
True Solution:	1.7861	1.7875	0.06	0.10
Case A:	1.7861	1.7875	0.06	0.10
Case B:	1.5756	1.3724	0.07	0.08

The total time to compute the results (Appendix E) from the sample data (Appendix D) was 16.36 seconds on the IBM 360/67 digital computer. The accuracy of the results is considered to be better than 1 part in 10,000 if the correct dips are entered. The propagated error gives no indication that the correct dips were entered or that the computed values represent the true interval sound speed. Only by subjectively analyzing the results can gross errors be realized.

IV. INSTRUMENTATION

A. THE WIDE-ANGLE REFLECTION SYSTEM

The system for recording wide-angle reflection data is shown schematically in Figure 6. The profile recorder, timer switch, sound source, amplifiers and filters are those components normally carried on board oceanographic survey vessels for collecting normal-reflection seismic profiles. For collecting wide-angle seismic reflections, a sonobuoy system was developed to be used in conjunction with the on-board components. The sonobuoy system included a radio sonobuoy, an antenna, and a radio receiver. The system was developed with emphasis on simplicity and low cost; however, the two were not always synonymous.

1. The Sonobuoy

The sonobuoy, launched while the ship was underway, performed as a self-contained station for detecting the sound pulses reaching that point in the ocean by various paths as shown in Figure 1. The pressure pulses were received by the hydrophone suspended below the sonobuoy by a thin wire. The pulses were converted to electrical signals and transmitted to the ship by the VHF radio transmitter contained in the watertight compartment of the sonobuoy. The sonobuoy transmitted on a pre-set frequency indicated by the channel number painted on the case. Table III lists the 31 sonobuoy channels available and the corresponding frequencies. The transmitter and acoustical amplifiers are powered by the sea-water-activated batteries located in the base of the housing

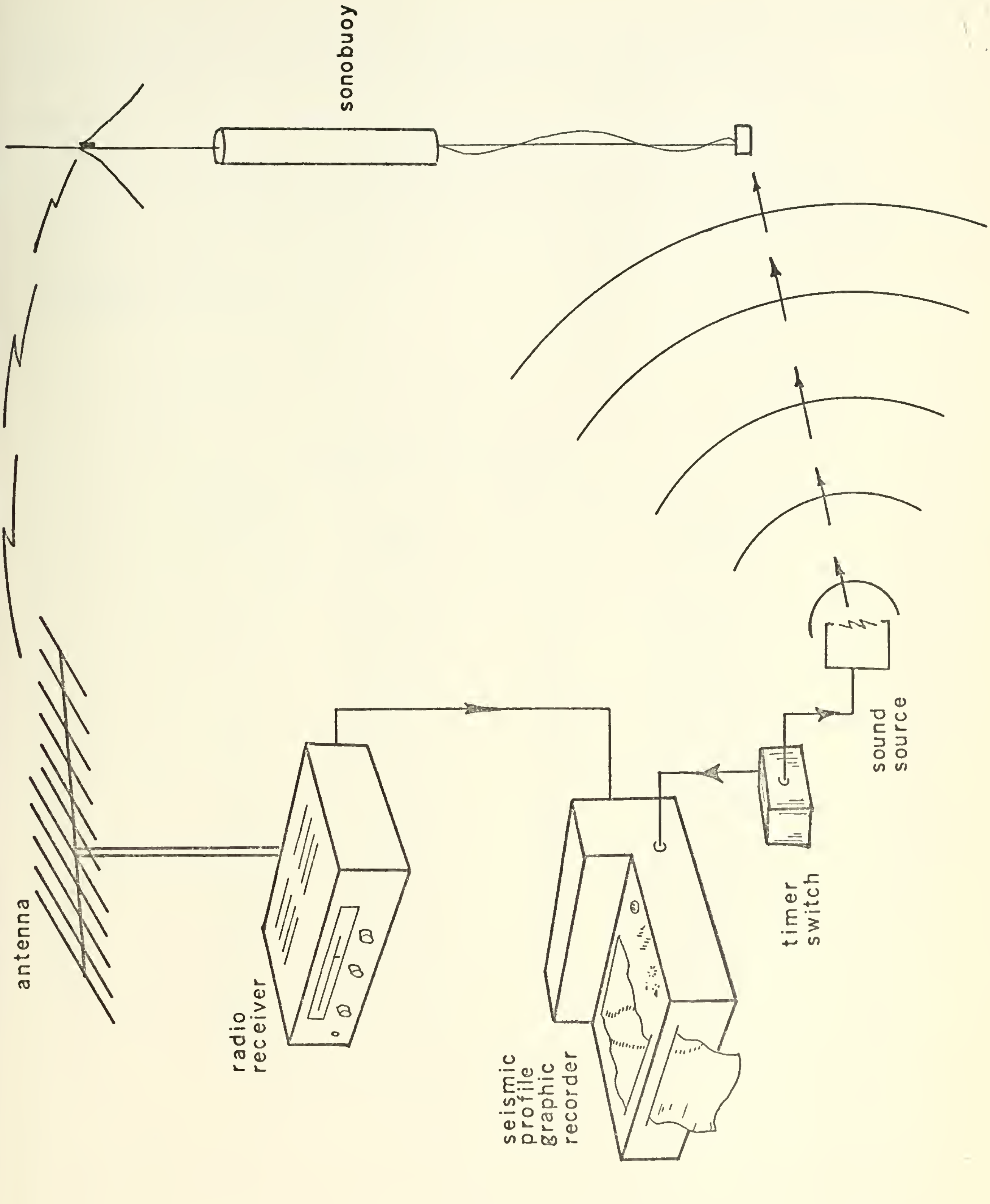


Figure 6. System for collecting wide-angle reflections

and become active within seconds after the sonobuoy contacts the water. The sonobuoys used were of the AN/SSQ-23A, AN/SSQ-41, and AN/SSQ-57 types. Figure 7 is a drawing of an AN/SSQ-57 sonobuoy as it would appear in the water showing the antenna and hydrophone package. The characteristics of the various types of sonobuoys used are listed in Table IV.

Table III

Sonobuoy Frequencies

Channel	Frequency MHz	Channel	Frequency MHz
1	162.25	17	162.625
2	163.00	18	163.375
3	163.75	19	164.125
4	164.50	20	164.875
5	165.25	21	165.625
6	166.00	22	166.375
7	166.75	23	167.125
8	167.50	24	167.875
9	168.25	25	168.625
10	169.00	26*	169.375
11	169.75	27*	170.125
12*	170.50	28*	170.875
13	171.25	29	171.625
14	172.00	30*	172.375
15	172.75	31*	173.125
16*	173.50		

* crystals available for radio receiver

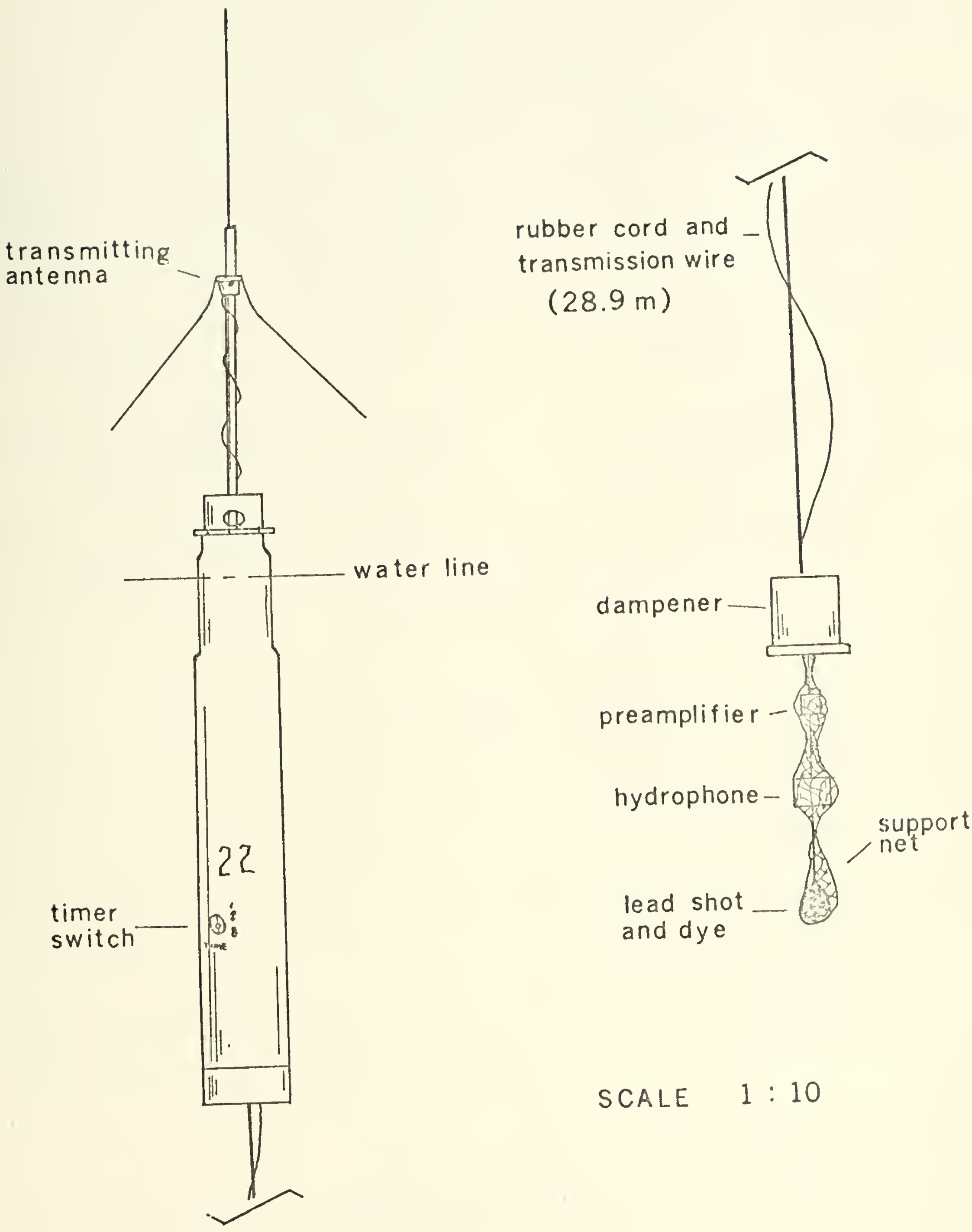


Figure 7. AN/SSQ-57 Sonobuoy

Table IV

Sonobuoy Characteristics

	AN/SSQ-23A	AN/SSQ-41	AN/SSQ-57
Weight, Kg	8.11	9.02	9.02
Channels	1 - 16	1 - 31	1 - 31
Time Selection, Hours	1	1 or 3	1 or 8
Depth of Hydrophone, Meters	18.2	18.2 or 90.1	28.9
Transmitter Power, Watts	1/2	1	1

Each sonobuoy has a water-soluble scuttling plug located above the center of the housing. When the plug dissolves, water enters the watertight compartment and the buoy sinks. The floating period of the sonobuoy is a function of water temperature, with the plug dissolving more rapidly in warmer water. In no case, however, is the floating period less than 8 hr nor more than 20 hr in the case of the AN/SSQ-57 type (Naval Air Systems Command, 1967).

The plug was sealed with waterproof tape when a study was conducted investigating modifications to be made to the sonobuoy for recovering and re-using it on subsequent stations. The study revealed, however, that the rubber gaskets used to seal the water tight compartment were not intended for long use and that small amounts of sea water entered

the compartment after only 3 or 4 hr of immersion. This was learned after a considerable amount of sea water was found inside one particular sonobuoy after it was in the water for about 12 hr. On another occasion, a sonobuoy operated successfully for 3 hr in the water before it was recovered. The salt water batteries were removed immediately to prevent any electrolysis or heating damage and the buoy was washed in a mild solution of soap and water. Later, however, it was found to be inoperable due to corrosion of the electronic components inside the watertight case. In each case, the scuttling plugs were sealed. Considering this, and also considering the problem of trying to recover 18 to 90 m of hydrophone wire, which had a strong tendency to kink, it was decided that the cost of using one sonobuoy per station was far less than the complications which would incur and the time involved to recover and re-use a sonobuoy.

The sonobuoys were launched by hand from the fantail of a ship. A screwdriver was used to bend the ends of the retaining ring on the bottom of the sonobuoy and release the bottom plate (Fig. 8). In some cases, the small screw used to secure the ring was removed and the entire retaining ring removed. Once the ring was removed, the bottom plate and hydrophone package were free to drop out of the sonobuoy, but were held in place until the sonobuoy was launched. The bottom plate serves as a weight to pull an aluminum protective housing away from the hydrophone package once the sonobuoy is in the water. For this reason, the clips (Fig. 9), which secure the plate to the housing, are not removed.

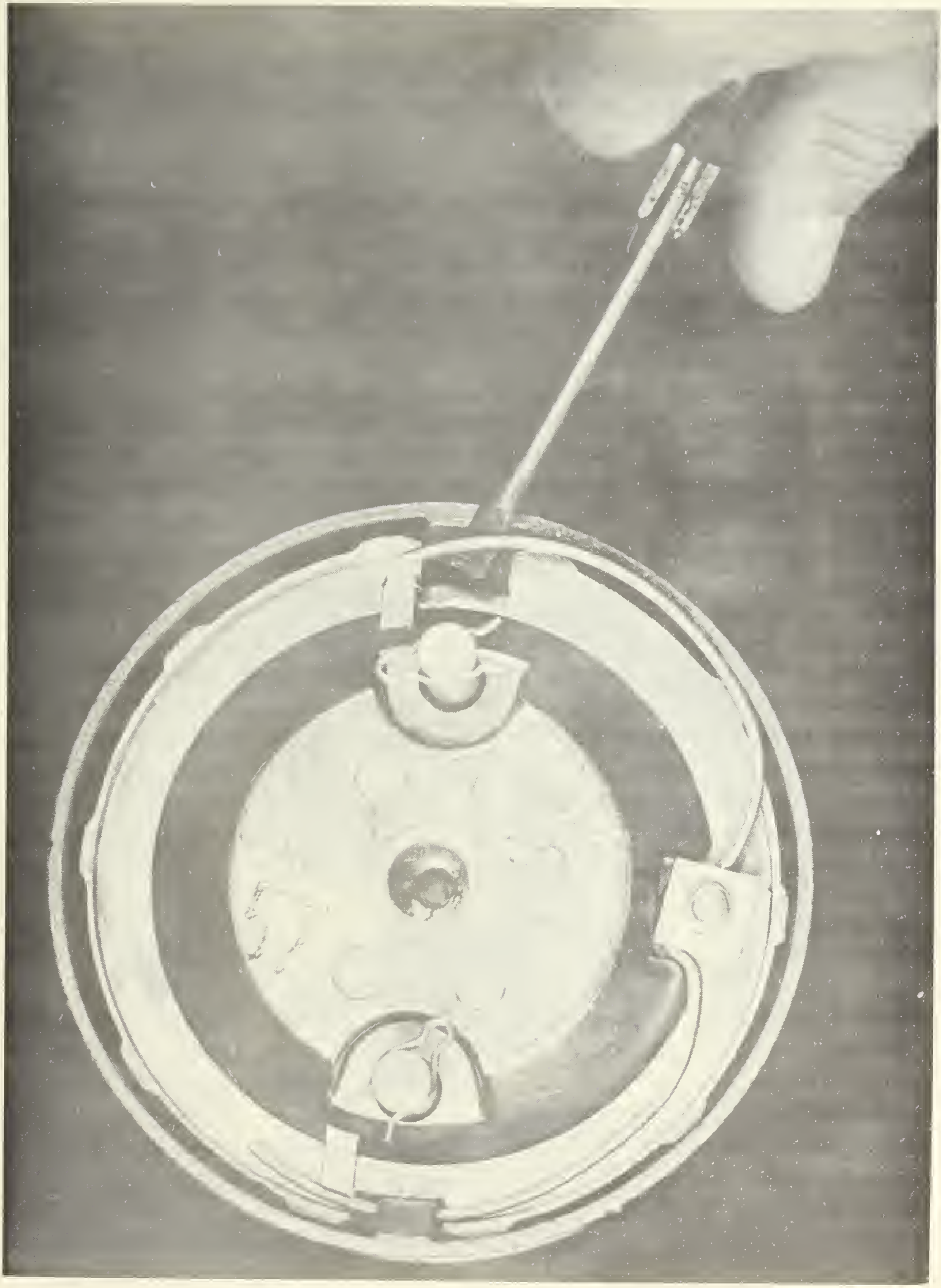


Figure 8. Releasing the bottom plate of the AN/SSQ-57 sonobuoy

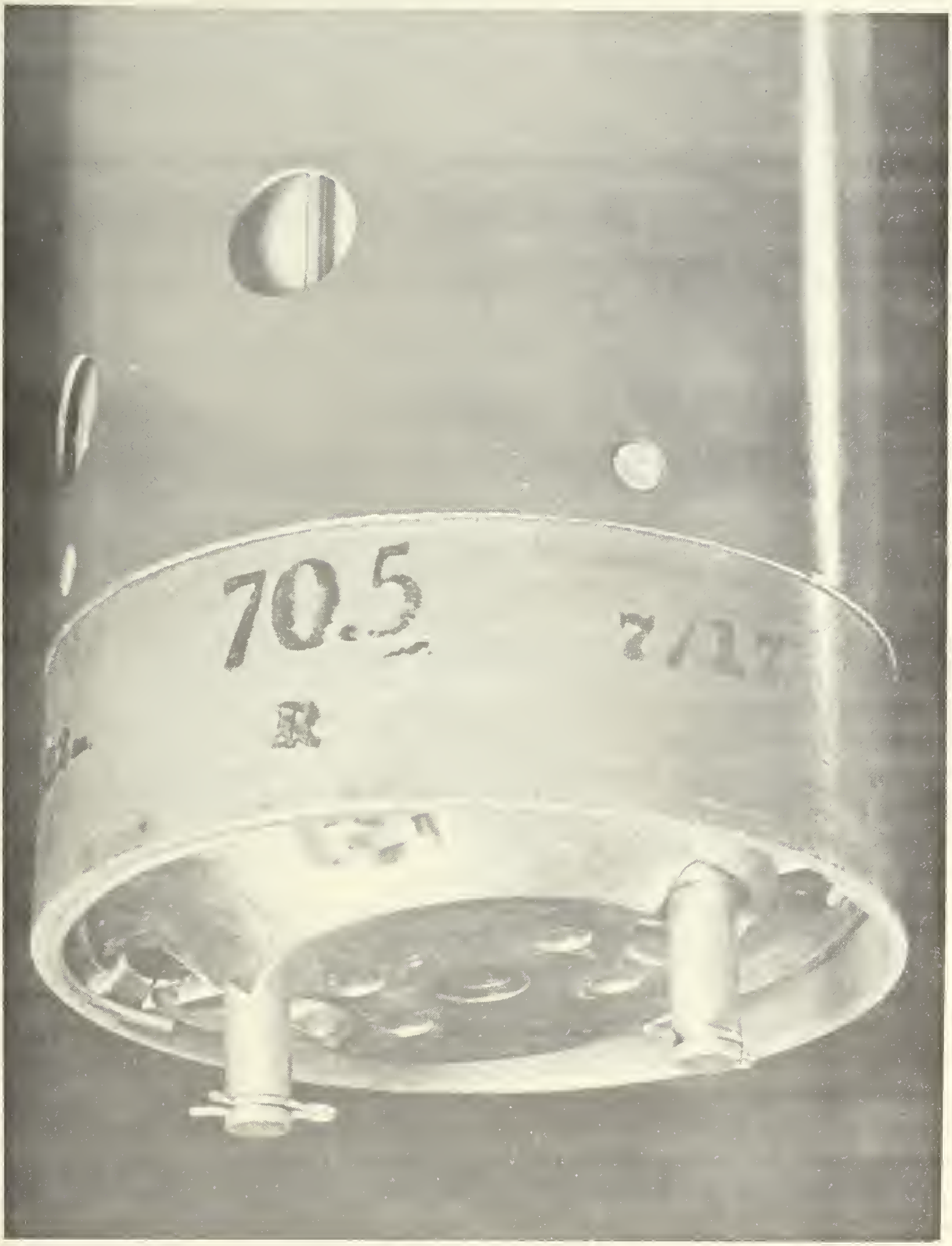


Figure 9. Bottom plate retaining clips

The next step was to release a second retainer ring located around and near the top of the sonobuoy. Considerable caution was warranted here as this ring allowed the rotochute assembly to fall free and pull a small white lanyard releasing the spring-loaded transmitting antenna. The antenna erects with sufficient force to cause injury. Once it was safe to do so, the retaining ring was released by lifting a small U-shaped pin (Fig. 10) and the rotochute assembly gently removed. A slight tug given on the lanyard tripped the antenna retainer clip allowing the antenna to extend to its full operating position shown in Figure 7. The sonobuoy was then ready to be launched.

2. Receiver System

A radio receiver and antenna system was used to receive and amplify the VHF signals transmitted by the sonobuoy. The radio used for this was a Japanese-made Realistic Patrolman pro-2 solid state VHF receiver. The decision to use this radio was based mainly on its availability at the time the study was started and the fact that its frequency band covered that of the entire sonobuoy range. Also of importance, and in keeping with the idea of simplicity and economy, the pro-2 was small, easy to carry, simple to operate, and relatively inexpensive ($99.00).

The pro-2 radio receiver is a self-contained unit operated on normal 110-V AC. An internal speaker was used to monitor the signals. The signal was tuned by manual control for maximum volume. Crystal operation was available, but did not appear to increase the quality of the signal. The crystal did, however, provide a means for tuning the

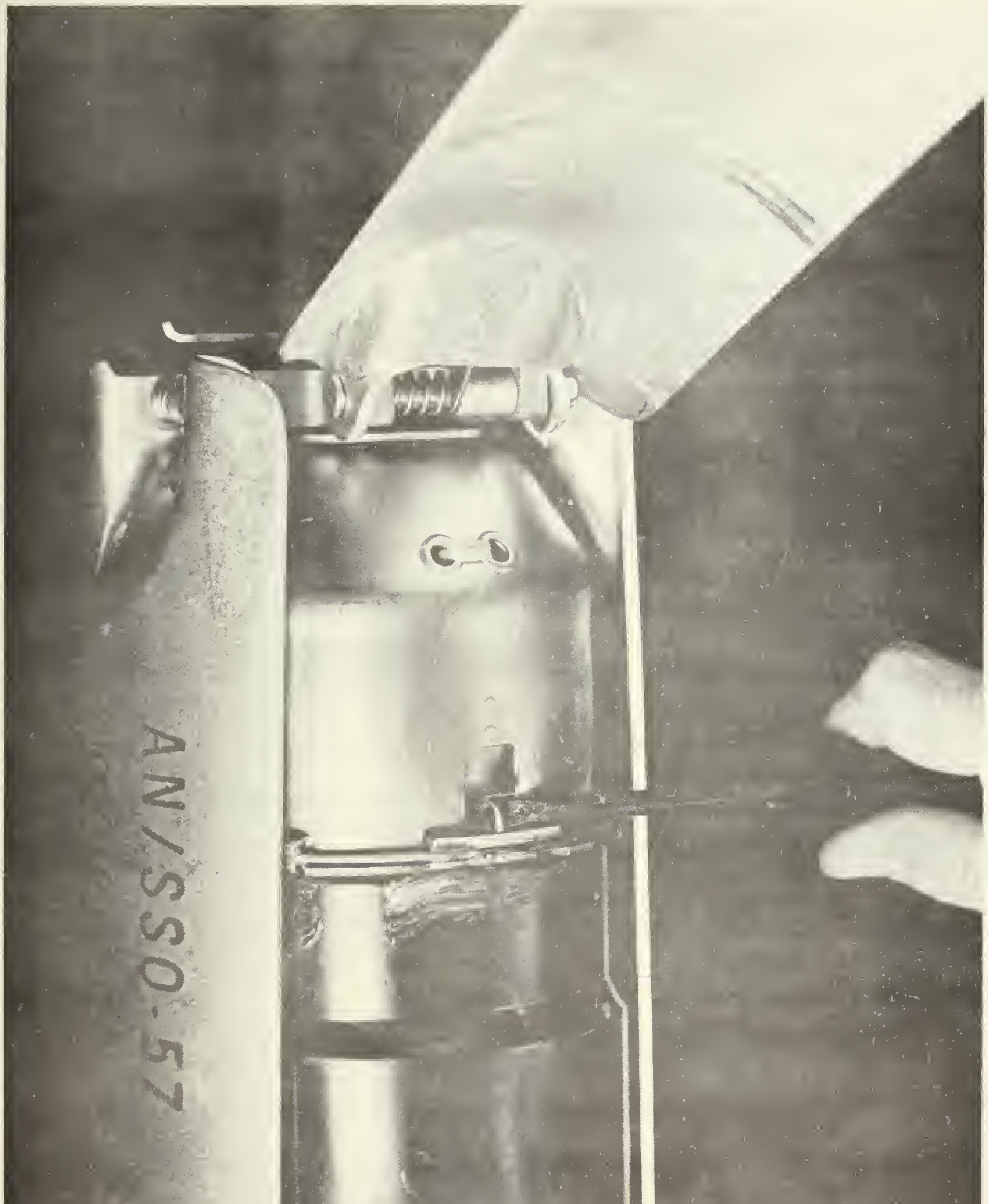


Figure 10. Removing the rotochute assembly

receiver without a signal present. With the proper crystal in place, the radio was simply tuned for maximum background noise. Crystals for the seven sonobuoy channels indicated in Table III were purchased from Radio Shack Warehouse, 2615 West 7th Street, Fort Worth, Texas.

The pro-2 receiver had two locations where the signal was available for recording. The signal taken from the speaker jack on the front panel of the cabinet was found generally to be highly distorted by the audio amplifier section of the receiver. The tape-out jack on the back of the cabinet provided a signal of rather low voltage, but when amplified it was found to be relatively undistorted. The results were further verified by using an oscilloscope to observe the wave form of the signal from each jack. A pure tone was transmitted from a signal generator and received by the radio. The signal at the tape-out jack was clear and undistorted while that of the speaker jack was either distorted at high volume settings or was lost in the amplifier noise at low settings.

An 11-element Winegard Yagi antenna (Fig. 11) was used with the pro-2 radio receiver for receiving the signal transmitted by the sonobuoy. The Yagi was purchased when the ground plane dipole antenna (salvaged from a used sonobuoy) failed to provide sufficient power gain for receiving the signal from the sonobuoy except at very small separation distances.

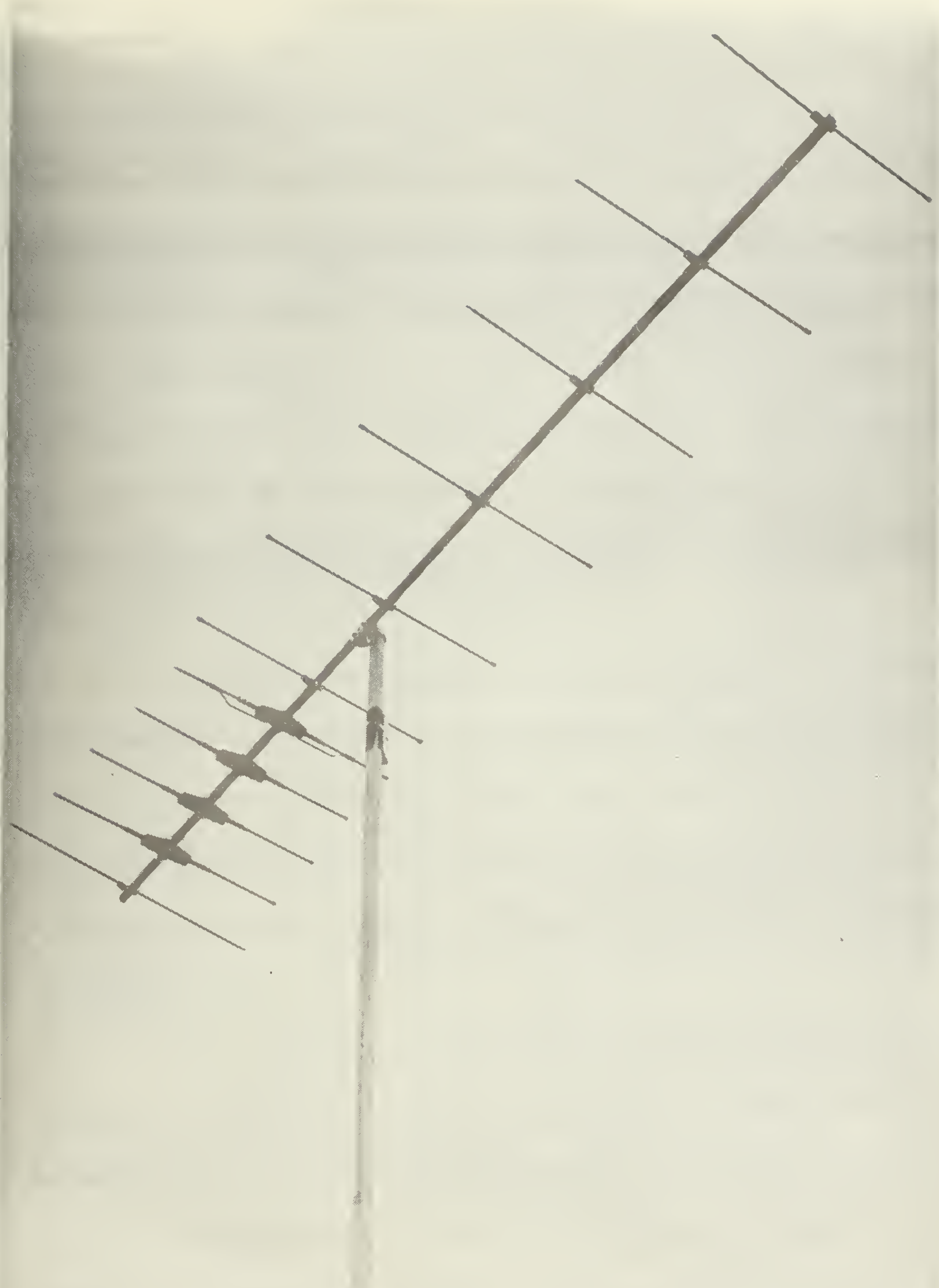


Figure 11. Yagi 11-element antenna

The antenna patterns for each antenna were recorded over a range of frequencies covering the sonobuoy range (Fig. 12). It can be seen from this graph that the Yagi was quite frequency-dependent and at lower frequencies did not produce better results than were obtained using the dipole antenna. Figure 13 shows the antenna pattern for the Yagi at various frequencies. The dipole antenna pattern was omni-directional over the entire sonobuoy frequency range. It was decided, therefore, that only higher frequency sonobuoys would be used and special attention would be given to insure that the Yagi antenna was pointed in the direction of the sonobuoy.

A 300/50-ohm impedance matching transformer was attached at the antenna to couple the 300-ohm antenna to the 50-ohm shielded cable. All external connections were covered with alternate layers of tape and electrical coating to prevent salt spray from damaging the system. A stainless steel pipe, 7-m long and 3.75 cm in diameter, was used for an antenna support.

The entire wide-angle reflection system weighed less than 10 kg per sonobuoy and was quite transportable; the whole system can be carried in the backseat of an automobile. It took only a few minutes to set up the equipment aboard ship. The system was simple to use, requiring little more than to launch a sonobuoy and to tune the receiver.

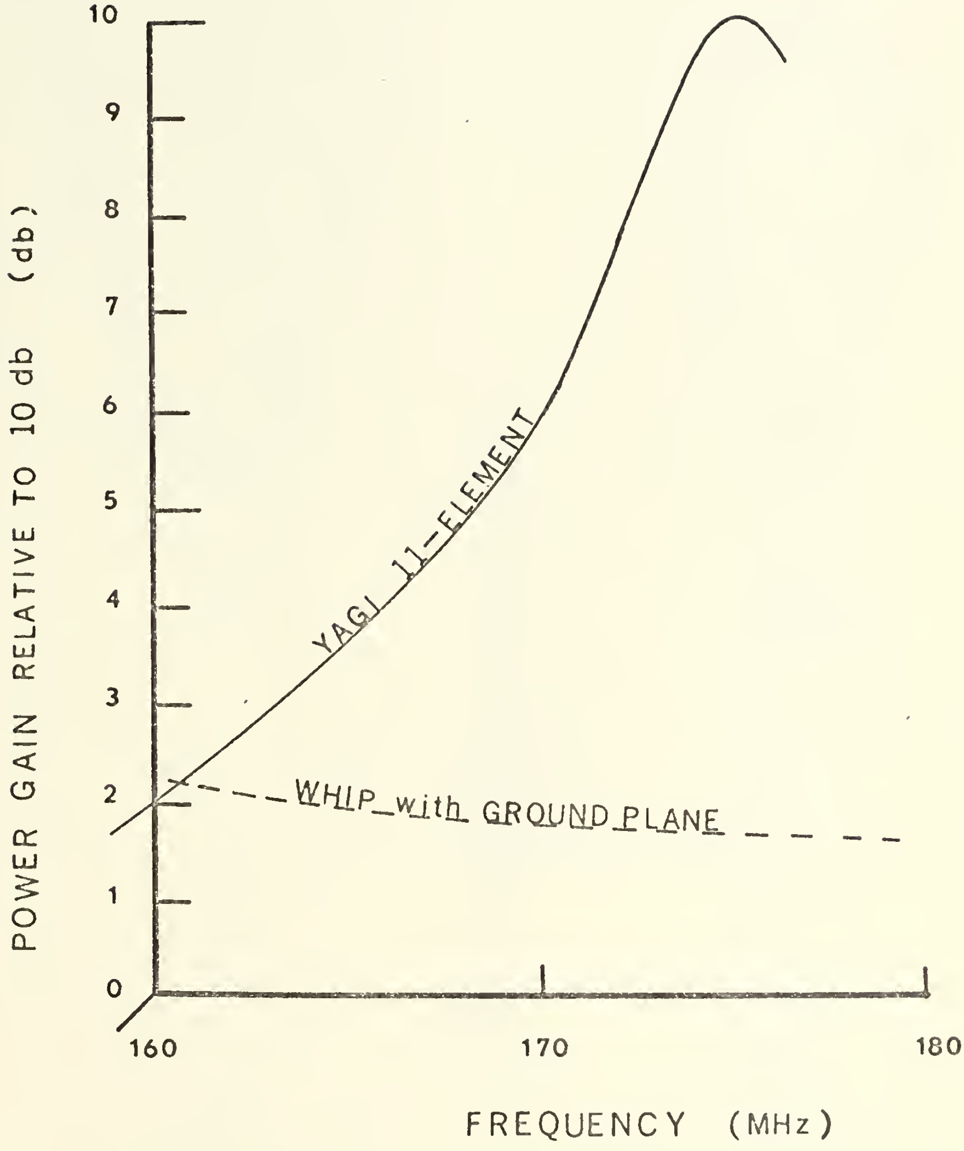


Figure 12. Power gain vs. frequency curve

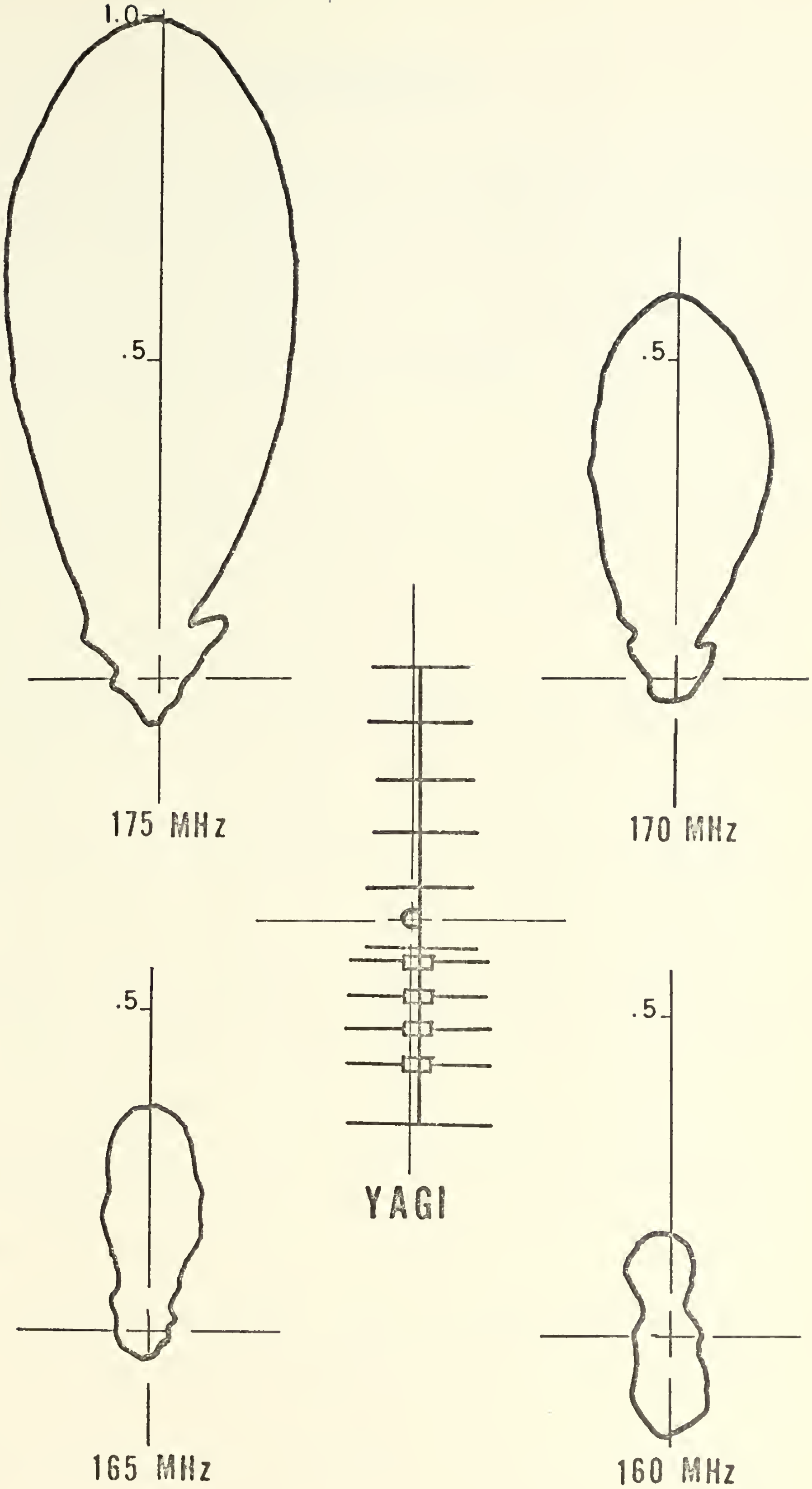


Figure 13. Antenna patterns for Yagi antenna at various frequencies (relative to 175 MHz)

V. CONCLUSIONS

It was found from this study that the Realistic pro-2 radio receiver, when used with a Winegard Yagi antenna, could adequately receive the VHF signal transmitted by a radio sonobuoy and at sufficient distance to conduct wide-angle seismic reflection profiling. It was further found that the signal received with this system was distorted by the audio amplifier section of the radio. An undistorted signal was available at the tape-out connection on the back panel of the pro-2 receiver cabinet, by-passing the audio amplifier section.

It was concluded after becoming familiar with three types of radio sonobuoys that, when used normally, they were quite simple to operate; but any modifications that were possible required a considerable amount of preparation in order to use the sonobuoy for more than one station.

Magnetic tape recordings have been made of the signal received using the sonobuoy system and the sample set of data from LGO demonstrated that the HONDO I computer program adapted for use with the system was able to reduce wide-angle reflections and obtain the interval sound speeds and corresponding thicknesses of sub-bottom layers.

It is concluded, therefore, that the system developed can be used to collect wide-angle seismic reflection data and that the HONDO I program can be used to reduce the data.

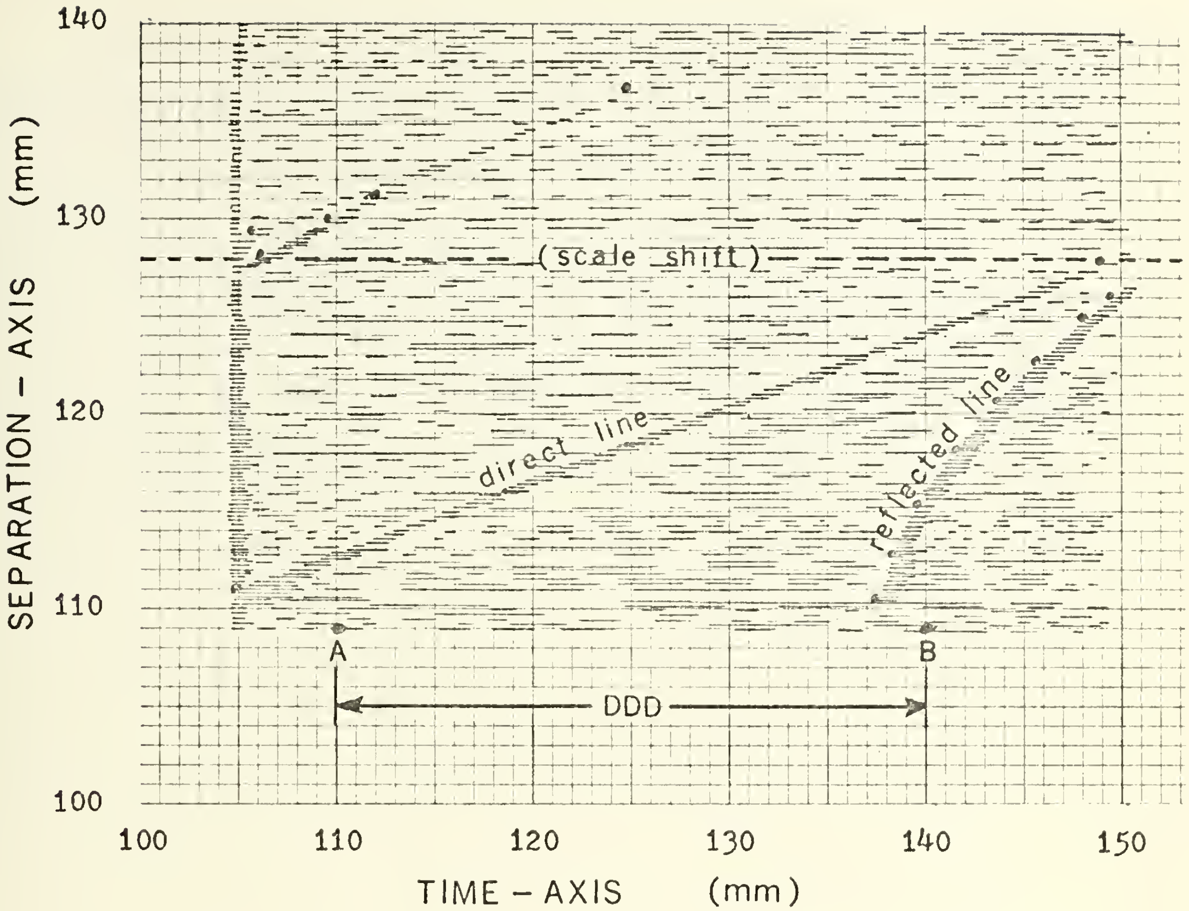
APPENDIX A

DIGITIZING THE WIDE-ANGLE REFLECTION RECORD

If T_O is marked on the record (the instant when the sonobuoy and sound source are together), this point becomes the origin. Otherwise, the direct travel time line, called the direct line, is extended to intercept the X-axis, thus defining the origin. A plastic overlay is placed over the record so as to include the origin and all direct and reflected traces within the millimeter-size grid etched on it.

Figure 14 shows a sample record with a direct line and one reflected trace. The origin of the grid does not coincide with the origin of the record, but rather the entire data is included under the grid. Below the record are sample values read from the record, including the two points A and B used to set the time scale. Points A and B are selected anywhere along the T-coordinate and are a measure of the distance in millimeters from the origin of the grid in the T-direction only. The time DDD represents the known time interval between the two points.

The values from the direct line are recorded in eight-digit integer form. For example, a point located at 127.9 mm from the grid origin on the X-scale and 148.9 mm on the T-scale is recorded as 12791489. The X-scale is the vertical scale and represents the first four digits, while the T-scale is horizontal and represents the last four. From two to six points can be used to represent the direct line. The reflection traces are digitized similarly, except that as many as 90 points can be used. The program can handle up to 10 reflecting horizons.



Direct line:	11101049 12791489 12931056 13781248
Reflected line:	11041373 11291382 11531395 11811414 12801438 12281458 12501480 12611493 12811060 13001095 13111120
Point A:	110.0
Point B:	140.0
DDD:	3 seconds

Figure 14. Digitizing the data

At times, the sound pulse is detected at the sonobuoy after the recorder completes a cycle. This occurs when the separation between the sonobuoy and the sound source becomes large enough so that the travel time for a particular sound wave is greater than the sweep rate of the recorder. An example of this is shown in Figure 14 where the trace goes off the bottom of the record and continues on the top during the next cycle. In this case, the shift is taken care of within the program.

APPENDIX B

ROUTINE FOLLOWED BY HONDO I COMPUTER PROGRAM

The computations begin in the MAIN routine by reading from the first card in the data deck the station identification, ADEN1 and ADEN2, and the number of layers or reflections observed, NREF, for the particular station. Subroutine TRIALS is then called to enter the valves for the trial solutions which include trial sound speeds V from the second card in the data deck and the trial dips W from the third card. Only NREF values are taken from each card and blank spaces are read as zero. As an example, for the sample station DIANNE (Appendix D), the card representing the trial dips is blank; therefore, the trial dip for each of the three layers is zero. The technique of reading zeros from blank cards is used throughout the program to control the exits from particular subroutines. For this reason, it is extremely important that a blank card follow the cards containing the digitized data pairs for the direct trace and for each reflected trace, and that an additional blank card follow the data from the last layer of the last station investigated. This additional blank card causes the program to exit the computer and completes the job. The blank card after each set of data points tells the computer that there are no more points for that particular trace.

The fourth card in the data deck is also read by TRIALS. The card contains the value of the computed sounding speed VV for the water layer. This value will replace the value read in as a trial speed for this layer.

Thus, the first number in the array labeled V is the actual value used for the sounding speed VV of the first, or water, layer. Also, the dip read for the first layer is not, in fact, a trial dip; but rather it represents the actual value determined for the sea floor. For this reason, the values entered for the first layer of sounding speed VV and dip W must be those values computed from observations made at the time the data were collected.

Values for V and W are transferred back to MAIN through COMMON.

The program is returned to MAIN and the main loop for NREF layers begins by setting the integer L equal to 1 for the first layer. MAIN then calls both subroutines READS and INTERP in succession.

For the first layer, READS enters the values from the fifth data card representing the constants which appear in Figure 14. They include two arbitrary points on the time scale A and B, the time in seconds represented by the distance between them (DDD), the seconds required for each sweep of the recorder (SPS), and finally, DELAY, which is a provision to include any time delay which might occur between the shot and the start of the recorder sweep. READS uses A, B, and DDD to scale the time axis in seconds. SPS is used to add the appropriate number of seconds to each point of the trace if the trace is continued at the top of the record during a scale shift.

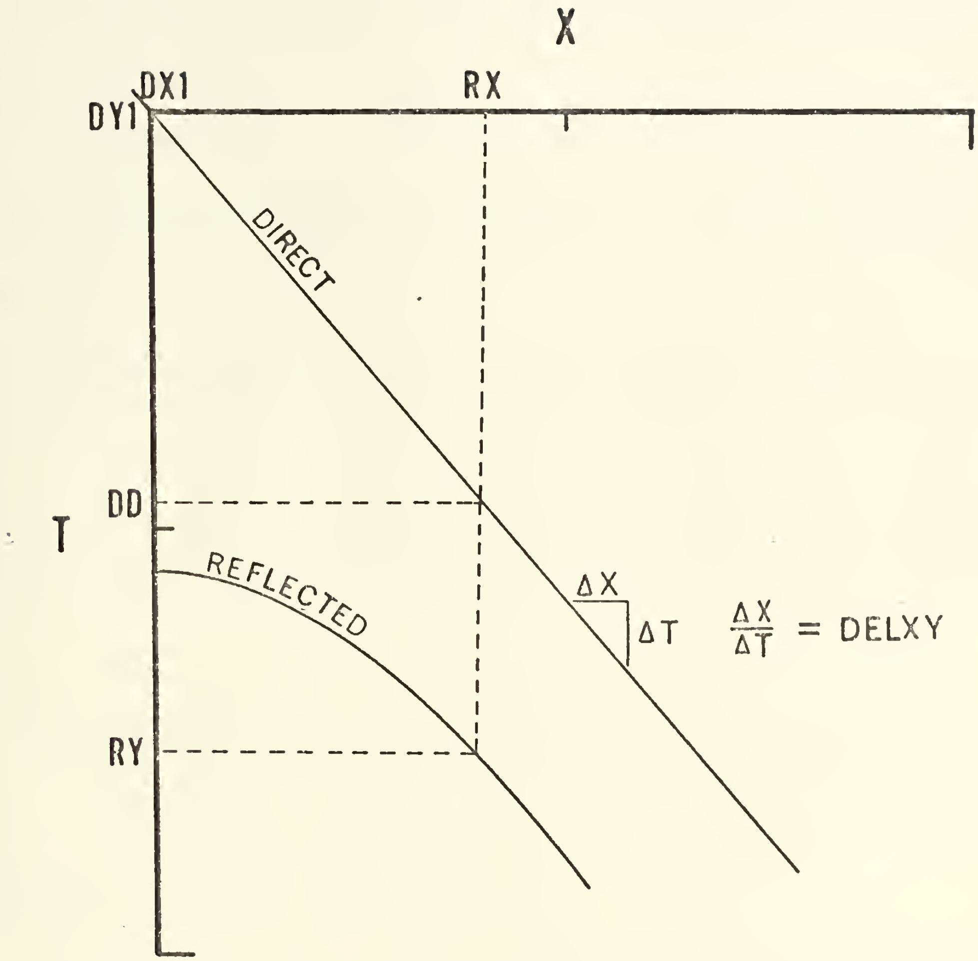
Once the time axis is scaled, READS then enters the digitized data points from the direct travel time trace. These points are converted to DX in millimeters and DY in seconds from the origin.

Next, READS enters the digitized points from the first reflected time trace and converts these points to RX and RY (in millimeters and seconds, respectively, from the origin).

Subroutine COUNT is called from subroutine READS to count the number of non-zero data points found on each card. The total number of points for any reflected time trace is summed on II and carried via COMMON to other locations in the program. ND is the number of points used to compute the direct time line.

All values entered in READS are transferred to MAIN and then to INTERP through COMMON.

INTERP interprets RX in millimeters for DD in seconds of direct travel time corresponding to each reflected travel time RY. This is accomplished by computing the slope of the direct time line, DELXY, and multiplying it by the millimeters of separation between RX and the origin DX1 as shown in Figure 15. RX is then reset equal to DD at each point on the reflected trace. Thus, RX becomes the travel time corresponding to each reflected travel time RY. RX and RY are transferred to MAIN through COMMON as U and S respectively. In MAIN, the direct travel time corresponding to the first reflection time recorded is compared with the minimum allowable separation for considering a fourth-order polynomial fit to the data, DMIN. DMIN is equal to 0.3 sec. If the direct time is less than DMIN, subroutine LSFIT is called and the data are used to compute a fourth-order polynomial using a least-squares technique. If the data are not obtained at or near vertical incidence and the minimum



$$DD = DY1 + (RX - DX1) * DELXY$$

Figure 15. Relating direct travel time to corresponding reflected travel time

reflection time is greater than DMIN, the data are squared and a linear least-square polynomial is computed in subroutine LSFIT. In either case, the data are extrapolated to T_o using the resulting polynomial equation,. the minimum reflection time is obtained, and the depth is computed using the sounding speed.

Subroutine LSFIT also computes the theoretical reflection time corresponding to the measured direct time by solving for the equation of a line fitted to the T^2/X^2 data.

Back in the MAIN routine, the corrective term CON to be applied to the travel time is computed and subtracted from the total time for each point. Thus, the reduced times R and D are squared and LSFIT is called to fit the values to a linear least-squares line and compute the horizontal sound speed from the coefficient X(2).

This completes the computations for the first layer, having obtained the depth and horizontal sound speed. These results are printed and the program returns setting L equal to 2.

In successive layers, the program begins by calling the subroutine READS. The digitized data for the particular layer is read and converted to millimeters of separation and seconds of travel time from the origin. Subroutine INTERP is called, interpreting millimeters of separation for seconds of direct travel time as was done in the case of the first layer. Now, however, the horizontal sound speed is known and the separation can be converted to distance in kilometers by an equation equivalent to

Equation (5). The values of reflected times and corresponding values of horizontal separation are returned to MAIN through COMMON as S and U respectively.

In MAIN, the horizontal separation for the first point is compared with the minimum allowable separation for considering a fourth-order polynomial, DMIN. In this case, DMIN is 0.45 km, obtained from the product of an assumed horizontal sound speed of 1.5 km/sec and a minimum allowable separation time of 0.3 sec. If the first point is less than DMIN, the data are used in the subroutine LSFIT to compute the coefficients of a fourth-order least-squares polynomial. If the first point is greater than DMIN, the values are squared and used to compute a linear lease-squares equation, again in subroutine LSFIT. As was done for the first layer, the data are extrapolated to obtain the minimum reflection time for the particular layer being considered.

The derivative of the fourth-order polynomial with respect to the horizontal separation is used to compute the angle of emergence ZM ($\emptyset + \theta$ in Fig. 4) using an equation equivalent to Equation (33). If the minimum reflection time was previously computed using a linear fit to the data, subroutine LSFIT is called a second time to compute the coefficients of the fourth-order polynomial fit. ZM is a function of the slope (dT/dX) of the fourth-order curve. The curve is not restrained beyond the first and last points and its slope may become erratic there. For this reason, the angle of emergence is not computed for the first and last points.

Subroutine TUPPER is called and the thickness of the layer being considered is computed using the trial solution of interval sound speed and dip. The technique follows that given in the previous section for the first layer, using an equation equivalent to Equation (29).

Subroutine TUPPER uses the emergence angles to compute travel times TT in the layers above the layer for which a solution is sought. TT is computed using the previously-solved values of interval sound speed and dip for the upper layers. The corresponding values of horizontal separation are found in a similar way. The travel times and separations are transferred to MAIN as TR and DR respectively.

MAIN reduces the measured values of reflection time S and horizontal separation U to obtain D, the reduced value of horizontal separation, and R, the reduced reflected travel time. D is also adjusted for the sum of the dips of the upper layers by dividing by C, the cosine of the sum.

The reduced D and R corresponds to a single layer case as shown in Figure 3.

The travel time for each point is finally reduced to that of a flat-layer case by subtracting equations equivalent to Equations (10) and (15). The value R in the computer program is now the reduced time squared for the flat-layer case. The value D is also squared and the subroutine LSFIT is called to fit a line to the reduced values. The second coefficient X(2) of the linear equation obtained from the subroutine LSFIT is then used to compute the interval sound speed.

The dip of the layer W is corrected using the relation

$$\tan W = \frac{V}{V_a} \tan W_a ,$$

where the subscript 'a' indicates the values for the assumed trial solution.

This solution then replaces the original trial solution and the computations go back to computing a new thickness and start the second iteration. Upon completion of the second iteration, the solutions for the layer are printed and the routine starts a new layer.

The results are tabulated and printed for each layer in succession. A sample list of results for the theoretical station DIANNE are included in Appendix E.

The first line gives the station name, layer number, and number of points used by the programs to compute the results. The number of points considered may be less than are digitized due to rejection of points occurring before T_o or those resulting in negative reduced times. The first three columns of figures below the heading represent squared values of reduced separation and reduced reflected travel times corresponding to a flat-layer case. For the first layer, the square of the separation listed under the column labeled X2, are in seconds squared, whereas, for each of the following layers, they are in kilometers squared.

The columns labeled T2 MEASURED and T2 COMPUTED are the reflection times squared corresponding to the separation in the first

column. The measured values are those values read from the reflection curves and reduced to the flat-layer case. The computed values are from a least-squares curve fitted to the reduced data. The fourth column is the difference between the measured and computed values of the reduced reflection times.

The variance σ^2 of the data is computed from

$$\sigma^2 = \frac{1}{N-2} \sum_{N} (T^2 - T_c^2)^2 ,$$

where N is the number of points, T the observed times, and T_c the computed times. The standard deviation is the positive square root of the variance.

If many reflection profiles were to be taken at the same location, the variance of the interval sound speed about the mean can be calculated. However, with only a single set of data, the variance cannot be calculated in this way. Instead, the techniques used to compute the variance, or propagated error, for each interval sound speed is based on the variance of the coefficients for each point compared to those coefficients obtained with the least-squares fit.

APPENDIX C. HONDO I COMPUTER PROGRAM

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                        CC
CC                                                        CC
CC                       HONDO I                          CC
CC                                                        CC
CC     PROGRAM TO SOLVE FOR THE DEPTH, DIP AND INTERVAL   CC
CC     SOUND SPEEDS WITHIN THE SUBSURFACE LAYERS.         CC
CC                                                        CC
CC     THIS IS ACCOMPLISHED BY SOLVING THE WIDE ANGLE RE- CC
CC     FLECTION PROFILE BY REDUCING EACH LAYER TO A SINGLE CC
CC     FLAT LAYER CASE.                                   CC
CC                                                        CC
CC     ORIGINAL PROGRAM WAS PREPARED BY                   CC
CC     XAVIER LE PICHON OF LAMONT-DOHERTY GEOLOGICAL OBSER-CC
CC     VATORY OF COLUMBIA UNIVERSITY.  THE PRESENT PROGRAM CC
CC     WAS ADAPTED FOR USE ON THE IBM 360 BY S.K. EDLESON CC
CC     LCDR,USN AT THE NAVAL POSTGRADUATE SCHOOL, MONTEREY,CC
CC     JULY, 1970.                                        CC
CC                                                        CC
CC                                                        CC
CC                                                        CC
CC                  THE FOLLOWING INPUTS                  CC
CC                  ARE REQUIRED:                         CC
CC                                                        CC
CC CARD   COLUMNS                                         CC
CC ----   -------                                         CC
CC                                                        CC
CC  1     1-8      STATION IDENTIFICATION                 CC
CC        14-15    NUMBER OF LAYERS (RIGHT ADJUSTED)      CC
CC                                                        CC
CC  2     1-10,ETC TRIAL SOUND SPEEDS FOR EACH LAYER IN   CC
CC                 KM/SEC.  MORE THAN ONE CARD MAY BE     CC
CC                 USED , BUT IN NO CASE CAN THERE BE     CC
CC                 MORE THAN TEN LAYERS.                  CC
CC                                                        CC
CC  3     1-10,ETC TRIAL DIPS (DEGREES PLUS OR MINUS)     CC
CC                                                        CC
CC  4     1-10     COMPUTED SOUNDING SPEED IN KM/SEC      CC
CC                                                        CC
CC  5     1-6      ANY REFERENCE MARKING ON R-TIME SCALE. CC
CC                 (ENTERED IN MM AND TENTHS,I.E. 102.4MM CC
CC        7-12     ANOTHER MARK ON R-TIME SCALE.          CC
CC        13-18    NUMBER OF SECONDS BETWEEN ABOVE TWO    CC
CC                 MARKINGS                               CC
CC        19-24    NUMBER OF SECONDS PER CYCLE            CC
CC        25-30    TIME DELAY BETWEEN RECORDER AND SHOT   CC
CC                                                        CC
CC  6     3-10,    DIGITIZED DATA PAIRS READ OFF D-LINE.  CC
CC        13-20,   FIRST FOUR NUMERALS ARE MM & 1/10 *10  CC
CC        23-30,   FROM X-TIME SCALE AND SECOND FOUR THE  CC
CC        33-40,   SAME FROM THE R-TIME SCALE: I.E. IF A  CC
CC        43-50,   POINT IS (102.4, 237.1) IT IS ENTERED ACC
CC        ETC.     10242371.  USE AS MANY CARDS AS NEEDED.CC
CC                 EACH POINT MUST BE GREATER THAN 100.0  CC
CC                                                        CC
CC  7              BLANK (DON'T FORGET BLANK CARDS, THEY  CC
CC                          ARE IMPORTANT)                CC
CC                                                        CC
CC  8     1-8      STATION IDENTIFICATION                 CC
CC        11-15    NUMBER OF LAYER THE FOLLOWING DATA     CC
CC                 REPRESENTS (RIGHT ADJUSTED). THIS CARD CC
CC                 IS REQUIRED FOR EACH LAYER             CC
CC                                                        CC
CC  9     3-10,ETC DIGITIZED DATA FROM ONE LAYERS R-LINE, CC
CC                 ENTER SAME AS D-LINE DATA              CC
CC                                                        CC
CC                 BLANK CARD REQUIRED BETWEEN EACH LAYER CC
CC                 AND TWO BLANK CARDS ARE REQUIRED AFTER CC
CC                 THE LAST LAYER OF THE LAST STATION.    CC
CC                                                        CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

HONDO I

MAIN ROUTINE

```
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSIONTO(10),HH(10),V(10),W(10), SW(10),XXXX(25),
     1CW(10),TW(10),D( 90),R( 90),ZM( 90),P(5,6),X(5)
      DIMENSION  U( 90), S( 90),DX(25),DY(25),TI(90),DOL(10)
      COMMON TO,HH,V,W,TR,DR,SW,CW,TW,D,R,ZM,P,C,SVN,VH
      COMMON X,TIT,U,S,XXXX,        DY,DXO,DYO,YSCAL,SGN
      COMMON M,IND,KO,IXXXX
      EQUIVALENCE(WW,DMIN)
C     READ IDENTIFICATION AND NUMBER LAYERS STATION
    1 READ(5,110)ADEN1,ADEN2,NREF
  110 FORMAT(2A4,2X,I5)
      IF (NREF.EQ.0) GO TO 9999
C     EXIT OUT OF ROUTINE IF NREF IS ZERO.  REQUIRES LAST
C     CARD BE BLANK.   ****NOTE****   LAST TWO CARDS IN
C     DATA DECK MUST BE BLANK.
   10 CALL TRIALS (KW,ADEN1,ADEN2,NREF,VV,PERCE)
C     MAIN DO LOOP FOR NREF LAYERS
C     READ IDENTIFICATION LAYER
      DO 12 L=1,NREF
  401 CALL READS(L,ADEN1,ADEN2,IREF,SPS)
      CALL INTERP (PERCE,ADEN1,ADEN2,IREF,L,SPS)
C     FIT CURVE TO DATA TO OBTAIN T-ZERO AND LATER
C     DIFFERENTIATE FOR ANGLE OF EMERGENCE
C     IND IS AN INDEX USED IN LSFIT SUBROUTINE
C     U IS NUMBER OF SECONDS OF DIRECT TRAVEL TIME CORRES-
C     PONDING TO S SECONDS OF REFLECTED TRAVE TIME.
  402 IF(L-1) 930,931,930
C     CHECK FOR DATA TO BE FITTED TO 4TH ORDER POLY: I.E.
C     DATA MUST BE COLLECTED BEFORE .45 KM OR .3 SEC SEPARAT
C     ION.  U(1) IS SEPARATION FOR FIRST DATA POINT.
  930 DMIN=0.45
      GO TO 932
  931 DMIN=0.3
  932 IF (U(1).LE.DMIN) GO TO 3
  923 IND=-1
      DO 90 K=1,KO
C     R AND D TAKE ON DIFFERENT VALUES CORRESPONDING TO
C     REFLECTED AND DIRECT TRAVEL TIMES RESPECTFULLY
      R(K)=S(K)**2
   90 D(K)=U(K)**2
      CALL LSFIT (1,L)
      TO(L)=DSQRT(X(1))
      IND=1
      IF(L-1)2,2,3
C     IF FIRST LAYER COMPUTE THICKNESS AND VH BY T2/X2
    2 CON=2.*TO(1)*DSIN (W(1))
      HH(1)=V(1)*TO(1)/2.
      DO 200 I=1,KO
C     BRING BACK TO FLAT LAYER CASE
      R(I)=S(I)**2+CON*U(I)
  200 D(I)=U(I)**2
      IND=1
      CALL LSFIT (1,1)
      VH=DSQRT(X(2))*V(1)
      GO TO 32
    3 DO 92 K=1,KO
      R(K)=S(K)
   92 D(K)=U(K)
      CALL LSFIT (4,L)
C     COMPUTE COEFFICIENTS OF THE DERIVITIVE FOR OBTAINING
C     THE EMERGENCE ANGLE ZM
      X(2)=X(2)*V(1)
      X(3)=X(3)*2.*V(1)
      X(4)=X(4)*3.*V(1)
```

```
      X(5)=X(5)*4.*V(1)
      CHECK = D(1)-DMIN
      IF (CHECK.GT.0.0) GO TO 920
  921 TO(L)=X(1)
  920 IF (L.LT.2) GO TO 2
C     FIND ANGLE OF EMERGENCE ZM FOR EACH POINT EXCEPT
C     FIRST AND LAST
  922 KO=KO-1
      IND=1
      DO 30 I=2,KO
C     ZM IS FIRST THE SINE OF THE ANGLE
      ZM(I)=X(2)+X(3)*U(I)+X(4)*U(I)**2+X(5)*U(I)**3
   30 ZM(I)=DARSIN(ZM(I))
C     ZM IS NOW THE ANGLE IN RADIANS.
      D(1)=-1.D20
      TI(1)=0.
   31 IND=-IND
      CON=2.*DSIN(W(L)) /V(L)
      IK=0
      DO 300 I=2,KO
C     COMPUTE TRAVEL TIMES IN UPPER LAYERS
      CALL TUPPER (L,ZM(I),IK)
      IK=1
C     REDUCE SEPARATION U TO SEPARATION FOR L LAYER ONLY
C     NOTE THAT D IS IN KM
      D(I)=U(I)-DR
C     REDUCE REFLECTION TIMES S FOR TIMES ONLY WITHIN L
      R(I)=S(I)-TR
      TI(I)=TIT
C     NOTE TIT IS T-ZERO. REFLECTION TIME FOR LAYER L ONLY.
C     CORRECT SEPARATIONS FOR DIPS OF UPPER LAYERS:
C     RECALL C IS THE COSINE OF THE SUM OF THE DIPS.
      D(I)=D(I)/C
C     ELIMINATE POINTS WITH NEGATIVE REDUCED D
      IF(D(I))300,3601,3601
C     REDUCE TO FLAT LAYER CASE
 3601 R(I)=R(I)**2+CON*D(I)*TI(I)-TI(I)**2
      D(I)=D(I)**2
  300 CONTINUE
C     SOLVE FOR SOUND SPEED
C     KW=1 FOR HORIZONTAL LAYERS:
C     KW=2 FOR DIPPING LAYERS.
      GO TO (5,6),KW
    5 IND=1
    6 CALL LSFIT (1,L)
      VV=V(L)
C     CHECK FOR IMAGINARY SPEED
      IF(X(2))3100,3101,3101
 3101 V(L)=DSQRT(1./X(2))
C     RESET ANGLE ACCORDING TO NEW SPEED
      TW(L)=TW(L)*V(L)/VV
      W(L)=DATAN(TW(L))
C     COMPUTE NEW THICKNESS HH.
      CALL TUPPER (L,ZM(2),0)
C     IF IND NEGATIVE RESTART PROCESS
      IF(IND)31,31,32
   32 WW=W(L)*0.572957795131D02
      WRITE(6,104)V(L),TO(L),SVN,WW
      IF(L.GT.1) GO TO 69
      DOL(L)=V(L)*TO(L)*500.0
      WRITE(6,105) DOL(L)
  105 FORMAT(' ',' DEPTH OF SEA FLOOR',T26,'=',F8.2,
     1T45,'METERS')
      GO TO 12
   69 DOL(L)=V(L)*(TO(L)-TO(L-1))*500.0
      WRITE(6,106) L,DOL(L)
  106 FORMAT(' ',' THICKNESS OF LAYER',I3,T26,'=',F8.2,
     1T45,'METERS')
  104 FORMAT(' ',' INTERVAL SPEED',T26,'=',F8.4,T45,'KM/SEC
     1'/' ',' T-ZERO REFLECTION TIME',T26,'=',F8.4,T45,'SEC
     1'/' ',' PROPAGATED ERROR',T26,'= +'/'+',T28,'_',D15.7,
     1T45,'KM/SEC'/' ',' DIP OF LAYER',T26,'= ',F7.4,
```

```
     1T45,'DEGREES')
  12 CONTINUE
     WRITE(6,111)VH
 111 FORMAT('1',' SPEED OF SOUND AT WATER SURFACE =',
    1T37,F7.3,' KM/SEC')
     GO TO 1
3100 WRITE(6,3200)L
3200 FORMAT('      SPEED NEGATIVE,REMOVE LAYER',I3)
9999 WRITE(6,9000)
9000 FORMAT('1')
     STOP
     END
```

SUBROUTINE TRIALS

```
C     READ TRIAL SPEEDS AND CORRESPONDING DIPS IN DEGREES:

      SUBROUTINE TRIALS (KW,ADEN1,ADEN2,NREF,VV,PERCE)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSIONTO(10),HH(10),V(10),W(10)
      COMMON TO,HH,V,W
   10 READ(5,107)(V(I),I=1,NREF)
      READ (5,107)(W(I),I=1,NREF)
  107 FORMAT(8F10.5)
      KW=2
      WT=0.
      DO 6000 I=1,NREF
 6000 WT=WT+DABS(W(I))
C     SET KW=1 IF LAYERS ARE HORIZONTAL:
C     USED IN HONDO I.
      IF(WT-1.D-10)6001,6001,6002
 6001 KW=1
 6002 WRITE(6,103)ADEN1,ADEN2,NREF
  103 FORMAT(1H1,'  STATION  ',2A4, ' NUMBER LAYERS  ',I3///
      WRITE(6,600)
  600 FORMAT(//'     TRIAL SPEEDS AND DIPS  '/)
      WRITE(6,500)
  500 FORMAT('0',8X,'TRIAL',3X,'TRIAL'/' ',
     1T2,'LAYER',3X,'SPD.',4X,'DIP  '/' ',
     1T10,'KM/SEC',2X,'DEGREES'/'+',
     1T2,5('_'),3X,6('_'),2X,7('_')/)
      DO 555 I=1,NREF
  555 WRITE(6,888) I,V(I),W(I)
  888 FORMAT(' ',I3,F11.4,F6.2)
C     CONVERT ANGLES TO RADIANS
      DO 1300 I=1,NREF
 1300 W(I)=W(I)/0.572957795131D02
C     READ MAIN CONSTANTS
      READ(5,105)VV,PERCE
  105 FORMAT(2F10.5)
C     VV IS SOUNDING SPEED
      V(1)=VV
      IF (PERCE.GT.0.1D-10) GO TO 1105
 1100 PERCE =1.0
 1105 WRITE(6,106)VV
  106 FORMAT('0',' SONIC SOUNDING SPEED =',F6.3,' KM/SEC')
      RETURN
      END
```

SUBROUTINE READS

```
C     THIS SUBROUTINE READS DIGITIZED TABLE OUTPUT OF
C     D-LINE AND R-CURVES.  CONVERTS RY AND DY TO SECONDS
C     RX AND RY ARE TRANSMITTED TO HONDO I BY COMMON AS
C     U AND S RESPECTFULLY.


      SUBROUTINE READS(L,ADEN1,ADEN2,IREF,SPS)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION RX( 90),RY( 90),DX(25),DY(25),IT(16)
      DIMENSIONTO(10),HH(10),V(10),W(10),SW(10),
     1CW(10),TW(10),D( 90),R( 90),ZM( 90),P(5,6),X(5)
      COMMON TO,HH,V,W,TR,DR,SW,CW,TW,D,R,ZM,P,C,SVN,VH
      COMMON X,TIT,RX,RY,DX,DY,DXO,DYO,YSCAL,SGN
      COMMON M,IND,II,ND
C     IF THE FIRST LAYER, READ IN THE D-POINTS IN ORDER TO
C     SCALE THE REFLECTED TIME SCALE
      IF(L-1) 1,1,3
    1 II=0
      READ(5,1002) A,B,DDD,SPS,DELAY
 1002 FORMAT(5F6.0)
      READ(5,889) (IT(I),I=1,12)
  889 FORMAT (6(2X,2I4))
      INDEX=1
      IT(13)=0
       DXO= IT(1)
C     COMPUTE YSCAL EQUAL TO NUMBER OF SECONDS OF RECORD
C     PER MILLIMETER OF MEASUREMENT OF THE REFLECTED
C     TIME SCALE
      YSCAL=DDD/(A-B)
      DYO=IT(2)
   20 CHECK = IT(3)-IT(1)
      IF (CHECK.GT.0.0) GO TO 22
   21 SGN=-1.
      GO TO 5
   22 SGN=1.
      GO TO 5
    3 II=0
      INDEX=2
      READ (5,1003) ADEN1,ADEN2,IREF    ,IR,DREF
 1003 FORMAT(2A4,2X,2I5,F10.3)
    4 READ(5,1004) (IT(I),I=1,16)
 1004 FORMAT(8(2X,2I4))
      IF(IT(1))5,6,5
    5 CALL COUNT(IT,N,3,15,2)
C     CONVERT Y TO SECONDS AND X TO MM FROM ORIGIN
      DO 204 I=1,N,2
  201 XX=IT(I)
      YY=IT(I+1)
      II=II+1
      GO TO (202,203),INDEX
  202 DX(II)=(XX-DXO)*SGN
      DY(II)=YSCAL *(DYO-YY)
      ND=II
      GO TO 204
  203 RX(II)=(XX-DXO)*SGN
C     CHECK FOR R BEFORE FIRST D AND ELIMINATE
      IF(RX(II)) 205,206,206
  205 II=II-1
      GO TO 204
  206 RY(II)=YSCAL*(DYO-YY)+DREF+DELAY
 5886 FORMAT(' ',D15.7)
  204 CONTINUE
      GO TO 4
C     FOR THE FIRST LAYER, BOTH THE D-POINTS AND THE
C     REFLECTION POINTS MUST BE READ IN.  IF "INDEX" IS
```

```
C       EQUAL TO ONE, THE D-POINTS HAVE NOT BEEN READ YET
      6 GO TO (61,65),INDEX
C       ADD NUMBER OF SECOND PER SWEEP (SPS) TO
C       DY IF DATA IS CONTINUED AT TOP OF RECORD
     61 DO 64 I=2,II
        CHECK = DY(I)-DY(I-1)+SPS/2.0
        IF (CHECK.GE.0.0) GO TO 64
     62 DO 63 J=I,II
     63 DY(J) = DY(J) + SPS
     64 CONTINUE
        GO TO 3
     65 RETURN
        END
```

SUBROUTINE COUNT

```
C       COUNTS THE NUMBER OF NON-ZERO ENTRIES PER CARD:

        SUBROUTINE COUNT(K,M,ISTAR,ISTOP,INT)
        DIMENSION K(1)
        DO 2 I=ISTAR,ISTOP,INT
        IF(K(I)) 2,1,2
      1 M=I-1
        GO TO 3
      2 M=ISTOP+INT-1
      3 RETURN
        END
```

SUBROUTINE INTERP

```
C     THIS SUBROUTINE INTERPOLATES D'S FOR R'S.
C     RX=U AND RY=S TRANSMITTED TO HONDO I BY COMMON
C     ADD NUMBER OF SECONDS PER SWEEP (SPS) TO
C     RY IF DATA IS CONTINUED AT TOP OF DATA


      SUBROUTINE INTERP (PERCE,ADEN1,ADEN2,IREF,L,SPS)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSIONTO(10),HH(10),V(10),W(10), SW(10),
     1CW(10),TW(10),D( 90),R( 90),ZM( 90),P(5,6),X(5)
      DIMENSION RX( 90),RY( 90),DX(25),DY(25)
      COMMON TO,HH,V,W,TR,DR,SW,CW,TW,D,R,ZM,P,C,SVN,VH
      COMMON X,TIT,RX,RY,DX,DY,DXO,DYO,YSCAL,SGN
      COMMON M,IND,II,ND
    6 DO 9 I=2,II
      CHECK = RY(I)-RY(I-1)+SPS/2.0
      IF (CHECK.GE.0.0) GO TO 9
    7 DO 8 J=I,II
    8 RY(J) = RY(J) + SPS
    9 CONTINUE
   60 J=1
C     INTERPOLATE D FOR R.
      DO 55 I=1,II
      IF(I-1) 50,52,50
   50 IF(RX( I)-DX( J)) 53,53,51
   51 IF(ND  -J) 53,53,52
   52 DX1=DX( J)
      DY1=DY( J)
C     COMPUTE SLOPE OF D-LINE BETWEEN EACH POINT
C     IN ORDER TO LINEARLY INTERPOLATE BETWEEN
C     EACH POINT
      J=J+1
      DELXY=(DY( J)-DY1)/(DX( J)-DX1)
C     DELXY IS SLOPE OF D-LINE BETWEEN J AND J+1 POINTS.
      GO TO 50
   53 DD      =DY1+(RX( I)-DX1)*DELXY
      RX(I)=DD*PERCE
C     RX(I) IS NOW THE SECONDS OF DIRECT TRAVE TIME
C     CORRESPONDING TO RV(I).
C     IF NOT THE FIRST LAYER, CONVERT D'S TO KILOMETERS
      IF(L-1) 55,55,54
   54 RX(I)=RX(I)*VH
   55 CONTINUE
      WRITE(6,101)ADEN1,ADEN2,IREF,II
  101 FORMAT('1',' STATION ',2A4,'   LAYER NUMBER',I2,
     1T38,' NUMBER OF READINGS',I3///)
      RETURN
      END
```

SUBROUTINE LSFIT

```
C     SUBROUTINE TO FIT T/X DATA TO FOURTH-ORDER LEAST-
C     SQUARE POLYNOMIAL OR FITS T2/X2 DATA TO A LINEAR LEAST
C     -SQUARE LINE:


      SUBROUTINE LSFIT (LL,L)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSIONTO(10),HH(10),V(10),W(10), SW(10),
     1CW(10),TW(10),D( 90),R( 90),ZM( 90),P(5,6),X(5)
      DIMENSION RX( 90),RY( 90),DX(25),DY(25)
      COMMON TO,HH,V,W,TR,DR,SW,CW,TW,D,R,ZM,P,C,SVN,VH
      COMMON X,TIT,RX,RY,DX,DY,DXO,DYO,YSCAL,SGN
      COMMON M,IND,KO
C     R CORRESPONDS TO REFLECTED TIMES
C     D CORRESPONDS TO REFLECTED TIMES
      IN=LL
      INO=IN+1
      NQ=INO+1
      KN=INO-1
      DO 1000 M=1,INO
      DO 1001 N=1,M
      P(M,N)=0.
      DO 1001 I=1,KO
      IF(D(I))1001,9001,9001
 9001 IF(M+N-2)6000,6000,6001
 6000 TX=1.
      GO TO 6002
 6001 TX=D(I)**(M+N-2)
 6002 P(M,N)=P(M,N)+TX
 1001 CONTINUE
      P(M,NQ)=0.
      DO 1000 I=1,KO
      IF(D(I))1000,9002,9002
 9002 IF(M-1)6003,6003,6004
 6003 TX=R(I)
      GO TO 6005
 6004 TX=D(I)**(M-1)*R(I)
 6005 P(M,NQ)=P(M,NQ)+TX
 1000 CONTINUE
      DO 1010 N=1,INO
      DO 1010 M=1,N
 1010 P(M,N)=P(N,M)
      DO 1022 K=1,KN
      DO 1002 I=1,K
      II=I+1
      KK=K+1
      A1=DABS(P(I,I))
      A2=DABS(P(KK,I))
      IF(A1-A2)1020,1021,1021
 1020 DO 1200 IIN=I,NQ
      AA=P(KK,IIN)
      P(KK,IIN)=P(I,IIN)
 1200 P(I,IIN)=AA
 1021 IF(A1-1.D-30)1002,1002,1210
 1210 DO 1201 NM=II,NQ
 1201 P(KK,NM)=P(KK,NM)-(P(I,NM)*P(KK,I)/P(I,I))
 1002 CONTINUE
 1022 CONTINUE
C     SOLVE MATRIX
      DO 1005 K=1,INO
      I=NQ-K
      II=I+1
      X(I)=P(I,NQ)
      IF(I-INO)1006,1050,1050
 1006 DO 1060 KX=II,INO
```

```
 1060 X(I)=X(I)-(P(I,KX)* X(KX))
 1050 A1=DABS(P(I,I))
      IF(A1-1.D-30)1500,1500,1005
 1005 X(I)=X(I)/P(I,I)
      A=IN+1
      IF(IN-1)1701,1701,4
 1701 IF(IND)4 ,4 ,21
   21 DDO=0.
      OK=KO
      IF (L.EQ.1) GO TO 69
      WRITE(6,696)
  696 FORMAT('0',3X,'ALL VALUES ARE REDUCED VALUES')
      WRITE(6,501)
  501 FORMAT(' ',1X,'X2',8X,'T2',8X,'T2',11X,'DIFF
     1'/' ',T13,'MEASURED',2X,'COMPUTED
     1'/'+',1X,8('_'),2(2X,8('_')),1X,14('_')/)
      GO TO 502
   69 WRITE(6,500)
  500 FORMAT('0',1X,'X2',8X,'T2',8X,'T2',11X,'DIFF
     1'/' ',T13,'MEASURED',2X,'COMPUTED
     1'/'+',1X,8('_'),2(2X,8('_')),1X,14('_')/)
  502 DO 1061 K=1,KO
      RR=0.
      IF(D(K))9003,9004,9004
 9003 OK=OK-1.
      GO TO 1061
 9004 DO 1062 I=1,INO
      IF(I-1)6006,6006,6007
 6006 TX=X(I)
      GO TO 1062
 6007 TX=X(I)*(D(K)**(I-1))
 1062 RR=RR+TX
      DK=R(K)-RR
      DDO=DDO+DK**2
      WRITE(6,1700)D(K),R(K),RR,DK
 1700 FORMAT(3F10.6,D15.7)
 1061 CONTINUE
      STU=OK
C     COMPUTE STANDARD DEVIATION:
C     STANDARD DEVIATION IS EQUAL TO THE SQUARE ROOT OF THE
C     VARIANCE.
      DDO=DSQRT(DDO/(STU-A))
      WRITE(6,1802)DDO
 1802 FORMAT('0',' STANDARD DEVIATION',T26,'=',D15.7
     1,T45,'SEC**2')
      STD=DDO
      VA=1./X(2)
      WRITE(6,1900)X(2),X(1)
 1900 FORMAT(' ',' SLOPE OF T2/X2 LINE',T26,'=',F9.5,'
     1'/' ',' T-ZERO INTERCEPT',T26,'=',F9.5)
C     SET STD EQUAL TO VARIANCE.
      STD=STD**2
      D11=0.
      D21=0.
      DO 6 M=1,KO
      IF(D(M))6,9010,9010
 9010 D2=D(M)**2
      D21=D2+D21
      D11=D(M)+D11
    6 CONTINUE
      D211=OK*D21-D11**2
      SX=STD/D211
C     COMPUTE THE VARIANCE OF THE INTERVAL SOUND SPEED.
      SVN=OK*SX
      SVN=SVN*VA**4
      SVN=DSQRT(SVN)
      GO TO 4
 1500 WRITE(6,1501)I,I
 1501 FORMAT(2HP(,I3,1H,,I3,24H)=0,PROBLEM UNDETERMINED)
    4 RETURN
      END
```

SUBROUTINE TUPPER

```
C     THIS SUBROUTINE IS USED TO REDUCE THE EFFECTS OF THE
C     UPPER LAYERS BY COMPUTING THE TRAVEL TIME IN THESE
C     LAYERS.  THE COMPUTED TIMES ARE TRANSMITTED TO HONDO I
C     WHERE THEY ARE SUBTRACTED FROM THE TOTAL TIMES TO
C     OBTAIN THE REDUCED TIMES.
C     NOTE THAT TI IS TRANSMITTED TO HONDO I AS TIT.


      SUBROUTINE TUPPER (L,ZZ,IK)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSIONTO(10),HH(10),V(10),W(10), SW(10),X(10),
     1CW(10),TW(10),D( 90),R( 90),ZM( 90),P(5,6),XX(10)
      DIMENSION RX( 90),RY( 90),DX(25),DY(25),Y(5)
      COMMON TO,HH,V,W,TR,DR,SW,CW,TW,D,R,ZM,P,C,SVN,VH
      COMMON Y,TI ,RX,RY,DX,DY,DXO,DYO,YSCAL,SGN
      COMMON M,IND,KO
C     CHECK IF FIRST POINT
      IF(IK)9990,9990,9991
C     FIND THICKNESSES   ,COMPUTE SIN COS TAN
 9990 DO 1000 I=1,L
      SW(I)=DSIN(W(I))
      CW(I)=DCOS(W(I))
 1000 TW(I)=SW(I)/CW(I)
      C=1.
      IF(L-1)1003,1003,1002
 1002 L1=L-1
      WW=0.
      DO 1001 I=1,L1
 1001 WW=WW+W(I)
      C=DCOS(WW)
C     FIND ANGLE OF REFRACTION IN UPPER LAYER CORRESPONDING
C     TO RAY REFLECTED NORMALLY FROM LOWER INTERFACE OF
C     LAYER CONSIDERED
 1003 I=L
      Q=W(I)
      IF(L-1)11,11,10
   10 Q=DARSIN((V(I-1)/V(I))*DSIN(Q))+ W(I-1)
      I=I-1
      IF(I-1)11,11,10
C     FIND ANGLE OF INCIDENCE Q AT UPPER INTERFACE OF I-1
C     LAYER.
   11 Q =Q-W(I)
      U=0.
      TT=0.
   12 IF(I-L)13,14,14
C     COMPUTE HH(I)
   13 HC=HH(I)-U*DSIN(W(I))
      SIX=DSIN(Q)
      COX=DCOS(Q)
C     COMPUTE HORIZONTAL SEPARATION FOR I-1 LAYER(U).
      U=U*CW(I)         +HC*SIX/COX
C     FIND ANGLE OF REFRACTION XW FOR NEXT LAYER UP FOR
C     ANGLE OF INCIDENCE Q FROM LAYER BELOW
      TT=TT+HC/(V(I)*COX)
      XW=DARSIN(V(I+1)*SIX/V(I))
C     FIND ANGLE XW MAKES WITH UPPER INTERFACE Q. Q BECOME
C     NEW ANGLE OF INCIDENCE ON UPPER INTERFACE.
      Q=XW-W(I+1)
      I=I+1
      GO TO 12
   14 HC=(TO(I)/2.-TT)*V(I)
C     GET THICKNESS OF LAYER OF LAYER BEING CONSIDERED
      HH(I)=HC+U*SW(I)
 9991 I=0
C     COMPUTE ANGLE EACH RAY LEAVES SURFACE WITH RELATIVE TO
```

```
C       VERTICAL
        XX(1)=ZZ+W(1)
  924   I=I+1
        IF(L-I) 9252,9252,9250
 9250   SIX=DSIN(XX(I))
        IF(SIX-V(I)/V(I+1))9253,30,30
C       COMPUTE THE ANGLE OF ENTRY INTO THE LAYER FOR EACH
C       POINT:
 9253   SIXW=V(I+1)*SIX/V(I)
        XW=DARSIN(SIXW)
        XX(I+1)=XW+W(I+1)
        GO TO 924
 9252   I=L+1
        X(L)=XX(L)
  926   I=I-1
        IF(I-1)21,21,928
  928   X(I-1)=DARSIN(DSIN(X(I)+W(I))*V(I-1)/V(I))
        GO TO 926
C       MAIN COMPUTATION
   21   TT=0.0
        U=0.0
        I=0
   24   I=I+1
        HC=HH(I)-U*SW(I)
        SIX=DSIN(X(I))
        COX=DCOS(X(I))
        HK=HC*(SIX/COX)
        U=U*CW(I)       +HK
        TK=HC/(V(I)*COX)
        TT=TT+TK
        IF(L-I)252,252,24
  252   I=L+1
        HK=HK/DCOS(W(L))
C       COMPUTE REDUCTION TO REFLECTIONS TR AND SEPARATIONS DR
        TR=TK
        DR=HK
        TI     =(HC/V(L))*2.
        PP=U
   26   I=I-1
        RR=HH(I)-PP*TW(I)
        COX=DCOS(XX(I)-W(I))
        HK=RR*DSIN(XX(I))/COX
        PP=PP/CW(I)+HK
        TK=(RR*CW(I))/(COX*V(I))
        TT=TT+TK
        IF(I-L)262,261,261
  261   DR=DR+HK
        TR=TR+TK
  262   IF(I-1)27,27,26
   27   TR=TT-TR
        DR=PP-DR*C
    3   RETURN
   30   DR=-1.D20
        TR=0.
        TI=0.
        GO TO 3
        END
```

APPENDIX D. SAMPLE DATA

SAMPLE DATA

EACH LINE
REPRESENTS
ONE CARD

```
DIANNE            3
1.5          1.6          1.7

1.49
423.2 183.4  5.0    5.0    0.07
  43754680   47482849

DIANNE            1
  44142208   44422194   44592184   44712170   44842157   44952145   45072133   45142119
  45252108   45342093   45432081   45522066   45592056   45652045   45722031   45792017
  45852004   45931993   45991981   46071967   46131953   46171943   46261927   46321915
  46381903   46431890   46481878   46521867   46591853   46631840   46701827   46751814
  46811802   46851789   46921775   46961765   47001750   47051740   47101727   47161713
  47181702   47221688   47271676   47321663   47391650   47411637

DIANNE            2
  44731891   44891877   45041865   45151852   45231840   45331827   45431814   45531803
  45601791   45681778   45771765   45851749   45921739   46001727   46071715   46121701
  46201688   46271676   46341662   46411650   46491636   46521626   46591612   46641600
  46721585   46761575   46811562   46891551   46951534   47021522

DIANNE            3
  44971662   45121650   45241636   45341625   45441612   45531598   45641587   45731574
  45831559   45911547   45981535   46071523   46151510   46211497   46291485   46361474
  46451457   46521446   46571432   46631421   46711409   46751396   46831384   46901372
  46971357   47021345   47071332   47121319   47181309   47251294   47311280   47341270
```

APPENDIX E. RESULTS

STATION DIANNE NUMBER LAYERS 3

TRIAL SPEEDS AND DIPS

LAYER	TRIAL SPD. KM/SEC	TRIAL DIP DEGREES
1	1.5000	0.0
2	1.6000	0.0
3	1.7000	0.0

SONIC SOUNDING SPEED = 1.490 KM/SEC

STATION DIANNE LAYER NUMBER 1 NUMBER OF READINGS 46

X2	T2 MEASURED	T2 COMPUTED	DIFF
0.159342	27.293261	27.364615	-0.7135450D-01
0.470273	27.599118	27.672436	-0.7331870D-01
0.739195	27.818630	27.938668	-0.1200381D 00
0.965480	28.127409	28.162689	-0.3528046D-01
1.244668	28.415657	28.439085	-0.2342762D-01
1.508562	28.683037	28.700339	-0.1730136D-01
1.825360	28.951670	29.013968	-0.6229822D-01
2.024092	29.266656	29.210712	0.5594430D-01
2.357128	29.515341	29.540416	-0.2507517D-01
2.648469	29.856153	29.828843	0.2730971D-01
2.956782	30.130211	30.134071	-0.3860678D-02
3.282065	30.474544	30.456101	0.1844259D-01
3.546797	30.705186	30.718184	-0.1299866D-01
3.781881	30.959897	30.950917	0.8979450D-02
4.065679	31.285595	31.231876	0.5371908D-01
4.359744	31.612999	31.523000	0.8999903D-01
4.619971	31.918542	31.780623	0.1379184D 00
4.978674	32.178226	32.135738	0.4248841D-01
5.256501	32.462718	32.410785	0.5193265D-01
5.638670	32.796208	32.789131	0.7076253D-02
5.934096	33.131402	33.081603	0.4979869D-01
6.135238	33.371869	33.280732	0.9113680D-01
6.600064	33.758426	33.740908	0.1751772D-01
6.919376	34.049804	34.057026	-0.7222040D-02
7.246231	34.342435	34.380612	-0.3817707D-01
7.524372	34.660864	34.655971	0.4893397D-02
7.807751	34.956103	34.936515	0.1958790D-01
8.038226	35.227839	35.164684	0.6315428D-01
8.449623	35.575206	35.571966	0.3239169D-02
8.689317	35.899287	35.809262	0.9002419D-01
9.116848	36.224837	36.232516	-0.7679258D-02
9.428513	36.551857	36.541063	0.1079366D-01
9.809425	36.855026	36.918165	-0.6313904D-01
10.067556	37.184872	37.173714	0.1115725D-01
10.527353	37.541734	37.628912	-0.8717841D-01
10.794704	37.797678	37.893588	-0.9590993D-01
11.065407	38.183226	38.161583	0.2164246D-01
11.408500	38.441344	38.501244	-0.5990000D-01
11.756831	38.778199	38.846091	-0.6789265D-01
12.181743	39.142608	39.266752	-0.1241445D 00
12.325056	39.430125	39.408632	0.2149285D-01
12.614197	39.797577	39.694881	0.1026967D 00
12.980338	40.113893	40.057359	0.5653447D-01
13.351717	40.457981	40.425022	0.3295917D-01
13.880447	40.803539	40.948463	-0.1449240D 00
14.033398	41.150566	41.099885	0.5068182D-01

STANDARD DEVIATION	=	0.6389933D-01	SEC**2
SLOPE OF T2/X2 LINE	=	0.99000	
T-ZERO INTERCEPT	=	27.20687	
INTERVAL SPEED	=	1.4900	KM/SEC
T-ZERO REFLECTION TIME	=	5.2160	SEC
PROPAGATED ERROR	=	± 0.2328726D-02	KM/SEC
DIP OF LAYER	=	0.0	DEGREES
DEPTH OF SEA FLOOR	=	3885.94	METERS

STATION DIANNE   LAYER NUMBER 2   NUMBER OF READINGS 30

ALL VALUES ARE REDUCED VALUES

X2	T2 MEASURED	T2 COMPUTED	DIFF
0.048589	0.013895	0.019739	-0.5843729D-02
0.053972	0.008540	0.021427	-0.1288677D-01
0.058720	0.012488	0.022915	-0.1042654D-01
0.062745	0.020485	0.024176	-0.3691739D-02
0.068639	0.024050	0.026024	-0.1973458D-02
0.075737	0.026166	0.028249	-0.2083175D-02
0.084365	0.021904	0.030953	-0.9048658D-02
0.091527	0.029197	0.033198	-0.4001252D-02
0.101089	0.035198	0.036195	-0.9969851D-03
0.113960	0.037200	0.040230	-0.3030216D-02
0.127683	0.050201	0.044531	0.5669983D-02
0.141809	0.050976	0.048959	0.2016556D-02
0.160843	0.053300	0.054925	-0.1625625D-02
0.180489	0.059381	0.061084	-0.1702920D-02
0.196513	0.078500	0.066106	0.1239395D-01
0.226165	0.084194	0.075401	0.8792825D-02
0.256824	0.091382	0.085011	0.6370793D-02
0.292664	0.104789	0.096245	0.8543620D-02
0.334553	0.113446	0.109376	0.4070864D-02
0.391120	0.125347	0.127107	-0.1759564D-02
0.415052	0.143980	0.134608	0.9371501D-02
0.477440	0.161590	0.154164	0.7425848D-02
0.528239	0.181217	0.170087	0.1112972D-01
0.621924	0.201968	0.199453	0.2514526D-02
0.675188	0.221144	0.216149	0.4995322D-02
0.748504	0.248038	0.239130	0.8908204D-02
0.883215	0.262237	0.281356	-0.1911887D-01
1.000119	0.303986	0.318000	-0.1401421D-01

STANDARD DEVIATION	=	0.8283879D-02	SEC**2
SLOPE OF T2/X2 LINE	=	0.31345	
T-ZERO INTERCEPT	=	0.00451	
INTERVAL SPEED	=	1.7861	
T-ZERO REFLECTION TIME	=	5.8053	KM/SEC
PROPAGATED ERROR	=	± 0.5969477D-01	SEC
DIP OF LAYER	=	0.0	KM/SEC
THICKNESS OF LAYER 2	=	526.28	DEGREES
			METERS

STATION DIANNE LAYER NUMBER 3 NUMBER OF READINGS 32

ALL VALUES ARE REDUCED VALUES

X2	T2 MEASURED	T2 COMPUTED	DIFF
0.027340	0.002257	0.006382	-0.4125055D-02
0.025440	0.003936	0.005787	-0.1851366D-02
0.026635	0.003679	0.006161	-0.2482090D-02
0.030224	0.006926	0.007284	-0.3580794D-03
0.035604	0.014095	0.008968	0.5126746D-02
0.045221	0.010986	0.011978	-0.9923697D-03
0.055817	0.015926	0.015294	0.6310724D-03
0.070666	0.022306	0.C19942	0.2364083D-02
0.084917	0.027209	0.C24402	0.2807597D-02
0.099064	0.034296	0.028830	0.5466272D-02
0.119355	0.036131	0.035180	0.9506511D-03
0.139051	0.041973	0.041344	0.6286805D-03
0.154577	0.052730	0.046204	0.6526771D-02
0.175825	0.055410	0.052854	0.2556720D-02
0.194427	0.058062	0.058675	-0.6138641D-03
0.217424	0.066329	0.065873	0.4561286D-03
0.233800	0.066879	0.070998	-0.4119449D-02
0.244261	0.079904	0.074272	0.5631719D-02
0.255025	0.082052	0.077641	0.4411104D-02
0.265551	0.077297	0.080935	-0.3638214D-02
0.268851	0.089557	0.081968	0.7589049D-02
0.270837	0.081146	0.082590	-0.1443862D-02
0.266871	0.074851	0.081348	-0.6497523D-02
0.256989	0.072681	0.078256	-0.5574773D-02
0.246093	0.072250	0.074845	-0.2595132D-02
0.231927	0.072446	0.070412	0.2034689D-02
0.214524	0.070957	0.064965	0.5991575D-02
0.189585	0.054853	0.057160	-0.2307099D-02
0.155604	0.039932	0.046525	-0.6592660D-02
0.123375	0.026457	0.036438	-0.9981321D-02

STANDARD DEVIATION	=	0.4465388D-02	SEC**2
SLOPE OF T2/X2 LINE	=	0.31297	
T-ZERO INTERCEPT	=	-0.00217	
INTERVAL SPEED	=	1.7875	KM/SEC
T-ZERO REFLECTION TIME	=	6.2508	SEC
PROPAGATED ERROR	=	± 0.9520118D-01	KM/SEC
DIP OF LAYER	=	0.0	DEGREES
THICKNESS OF LAYER 3	=	398.16	METERS

SPEED OF SOUND AT WATER SURFACE =   1.483 KM/SEC

LIST OF REFERENCES

1. Clay, C. S., and P. A. Rona, 1965. Studies of seismic reflections from thin layers on the ocean bottom in the western North Atlantic. J. Geophys. Res. 70: 855-869.

2. Dix, C. H., 1955. Seismic velocities from surface measurements. Geophysics 20: 68-86.

3. Green, C. H., 1938. Velocity determination by means of reflection profiles. Geophysics 3: 295-305.

4. Houtz, R. E., and J. I. Ewing, 1963. Detailed sedimentary velocities from seismic reflection profiles in the western North Atlantic. J. Geophys. Res. 68: 5233-5258.

5. Jakosky, J. J., 1950. Exploration Geophysics. Trija Publishing Company, Newport Beach, California, 1195 p.

6. Knox, W., 1965. A deep-ocean sedimentary velocity function. J. Geophys. Res. 70(8): 1999-2001.

7. Le Pichon, X., J. I. Ewing, and R. E. Houtz, 1968. Deep sea sediment velocity determination while reflection profiling. J. Geophys. Res. 73(8): 2597-2614.

8. Naval Air Systems Command, 1967. Handbook operating instructions, Sonobuoy AN/SSQ-57. NAVAIR 16-30SSQ57-1, 7 p.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Professor R. S. Andrews Department of Oceanography Naval Postgraduate School Monterey, California 93940	5
4.	Department of Oceanography Naval Postgraduate School Monterey, California 93940	3
5.	LCDR S. K. Edleson USS NIAGARA FALLS (AKS-3) FPO San Francisco 96601	2

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Naval Postgraduate School Monterey, California 93940	UNCLASSIFIED
	2b. GROUP

3. REPORT TITLE

System to Detect and Reduce Wide-Angle Seismic Reflections at Sea

4. DESCRIPTIVE NOTES *(Type of report and, inclusive dates)*

Master's Thesis; September 1970

5. AUTHOR(S) *(First name, middle initial, last name)*

Stuart Kaufmann Edleson, Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1970	87	8

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Naval Postgraduate School Monterey, California 93940

13. ABSTRACT

A simple system was designed to collect wide-angle reflection records in order to investigate the interval sound speeds of the sediment layers in the ocean. The system consisted of a frequency modulated receiver, a cut-to-channel Yagi antenna, and a sonobuoy, used in conjunction with a precision sonic profile recorder and a triggered sound source. A computer routine for reducing the data was obtained and modified for compatibility with the system and use on the IBM 360/67 computer. The system was designed to be both inexpensive and simple to use without any loss of accuracy.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Seismic wide-angle reflection technique at sea						
Sonobuoy; use in conjunction with wide-angle seismic profiling						

Thesis 122448
E239 Edleson
c.1 System to detect
and reduce wide-angle
seismic reflections
at sea.